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TECHNICAL NOTE No. 6/70

SUBJECT

PROGRAMMED LOAD FATIGUE TESTS on NOTCHED AND WELDED SPECIMENS of Al-Zn-Mg ALLOYS

DATE MARCH 1970

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MILITARY ENGINEERING EXPERIMENTAL ESTABLISHMENT

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PROGRAMMED LOAD FATIGUE TESTS ON NOTCHED AND WELDED SPECIMENS OF Al.Zn.Mg ALLOY.

Foreword

The work described in this Technical Note was undertaken at the Welding Institute (formerly The British Welding Research Association) on behalf of MEXE under Agreement No. 70/GEN/9533. It continues and develops Cumulative Damage Research originally undertaken at MEXE on Bailey bridge panels, but uses the newer weldable medium strength Al.Zn.Mg alloys in a simple welded specimen form.

MEXE-TN-6/70

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Approved by: Superintendent	J G Whitman

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Date: 31st March 1970

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PROGRAMMED LOAD FATIGUE TESTS ON NOTCHED AND WELDED SPECIMENS OF Al:Zn:Mg ALLOY

By J.D. HARRISON and T.R. GURNEY*

$\Sigma \frac{n}{N}$ $\left(n/N\right)$

SUMMARY

The report describes constant amplitude and programmed load fatigue tests on notched and welded specimens in two high strength aluminium-zinc-magnesium alloys. It is shown that, with very few exceptions, the Miner-Palmgren hypothesis that $\Sigma\frac{n}{N} = 1$ consistently underestimates life. For the notched specimens using the basic quadratic programme $\Sigma\frac{n}{N}$ varied from 0.8 to 14.8. For welded specimens using the same programme the value of $\Sigma\frac{n}{N}$ varied much less and was approximately 2.6 to 7.0 for pulsating tension loading. Changes in the order of application of programme blocks had a negligible effect on the values of $\Sigma\frac{n}{N}$ obtained. However, both for half tensile and for alternating loading, lower values of $\Sigma\frac{n}{N}$ were obtained.

When a spectrum parallel to the constant amplitude S-N curve was used high values of $\Sigma\frac{n}{N}$ were obtained, except when the lowest stresses in the programme were omitted. This fact led to the belief that a possible reason for the high values of $\Sigma\frac{n}{N}$ is coaxing at the lowest stress levels in the programme.

1. INTRODUCTION

In the design of military bridges it is of prime importance to save weight, since such bridges must be capable of being transported easily and erected rapidly. Thus the relatively high static strength to weight ratio of weldable aluminium-zinc-magnesium alloys makes them attractive materials for the fabrication of military bridges. Under military conditions, although the problem of fatigue exists, a finite life is often acceptable so that, by using high strength materials, high design stresses can be employed and thereby weight can be saved. However, when military bridges are used for civilian purposes the problem of fatigue may become acute, since they may then be in use for sufficient periods to suffer a large number of stress cycles.

The stress at any given point in a structure under service loading conditions usually varies in a more or less random manner. In the case of a road bridge it will be a function of the weights of vehicles crossing the bridge, which can obviously vary widely both in magnitude and in the order of occurrence of heavy and light vehicles.

Although many methods have been suggested for estimating service life under mixed loading conditions [1,2] the simplest, and the most widely used, is the Palmgren-Miner[3] cumulative damage rule, which relates the life under random loading conditions to the normal constant amplitude S-N curve. This rule is based on the assumption that if a structure is subjected to n_1 cycles of stress S_1, under which the expected life to failure is N_1, then the cycle ratio $\frac{n_1}{N_1}$ is a measure of the fatigue life exhausted at that stress. The linear cumulative damage rule then states that, under a spectrum of stresses, failure will occur when:

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \dots + \frac{n_i}{N_i} = \Sigma\frac{n}{N} = 1$$

It is well known that this rule is not accurate under all conditions, and in fact values of the cumulative cycle ratio $(\Sigma\frac{n}{N})$ extending from at least 0.0033 to more than 30 have been reported in the literature [4]. However much of the data has been obtained in simple two level tests on plain and notched specimens and is not therefore of great value in providing guidance for designers. Nevertheless these tests have indicated some of the important variables in the problem of cumulative damage which are not accounted for by the linear cumulative damage rule. In particular it should be noted that the rule assumes that stresses below the so called fatigue limit of the particular detail under consideration do no damage (i.e. since $N = \infty$, $\frac{n}{N} = 0$), and also that the rule takes no account of the chronological sequence in which the stresses are applied. Both these assumptions are incorrect[4].

As far as welded joints are concerned relatively little experimental evidence is so far available, but most of it is encouraging in that the cumulative cycle ratios obtained have usually been greater than 1.0. Thus in three investigations [5,6,7] in which fillet welded joints in steel have been subjected to a pulsating tension quadratic spectrum, the value of the cumulative cycle ratio has been found to vary between about 0.9 and 2.9 (it should be noted that only one specimen gave a value less than 1.0). Tests [8] on transverse butt welds in steel subjected to a half tensile sinusoidal programme also gave values greater than 1.0. Nevertheless, although these results are encouraging, it will be appreciated that they are very limited, not only in

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numbers but also in scope. For example, they were all obtained with steel specimens under purely tensile loading.

The objective of the investigation reported below was to provide further information about the fatigue strength, under cumulative damage conditions, of welded joints in an aluminium-zinc-magnesium alloy and particularly to investigate the effect of the stress ratio of the applied stresses and the chronological sequence of the high and low stresses in the programme. In order to provide a basis for calculating the cumulative cycle ratio the investigation also involved carrying out fatigue tests under constant amplitude loading. The effect of welding per se was investigated by carrying out comparative tests on notched and welded specimens.

2. TEST SPECIMENS

2.1. Material

In the course of the investigation two materials have been used. All the early work was carried out using material manufactured to the Alcan specification D74S GB. However, when it was found that stress corrosion cracking problems occurred with this alloy, subsequent work was carried out on material to High Duty Alloys specification H48.

Both materials were supplied in the form of 5 in. x 3/8 in. and $1\frac{1}{2}$ in. x 5/16 in. extrusions with 1/32 in. radii on the corners. The 5 in. x 3/8 in. D74S material came in two batches and there was some variation from batch to batch in chemical analysis and mechanical properties. The $1\frac{1}{2}$ in. x 5/16 in. D74S material came in three batches but was much less variable, having an identical analysis in all three batches and only slight variation in mechanical properties. The properties of the H48 material were somewhat better than those of the D74S material.

The chemical analysis of each batch of D74S material and of the H48 material is shown in Table 1. Table 2 gives details of the mechanical properties of both batches of the 5 in. x 3/8 in. D74S material and of the 5 in. x 3/8 in. H48 material, but only the range of results for the $1\frac{1}{2}$ in. x 5/16 in. D74S extrusions. Also shown in Table 1 and 2 are BWRA check test and analysis for D74S, the results of which seem to be in fair agreement with the manufacturers' figures. Table 3 gives details of the heat treatment used.

The SIGMA welds in the D74S and H48 materials were made with 1/16 in. dia. Al.5%.Mg wire to NG6 and NG61 specifications respectively.

2.2. Specimen form and manufacture

Details of the notched and welded specimens are shown in Fig.1a and 1b respectively. In the former the central notch, which consisted to two adjacent 1/8 in. diameter drilled holes with two 1/16 in. diameter holes forming a transverse slit, gave a theoretical stress concentration factor of 4.5. The intention was that the notch should give approximately the same fatigue behaviour as the non-load-carrying fillet welded detail used for the welded specimens, and the notch indicated above was arrived at after some experimentation. It will be seen later that, although the slopes of the S-N curves for the welded and notched specimens were very different, their fatigue strengths under pulsating tension loading were approximately the same in the region of 2-3 x 10^5 cycles.

The choice of the form of welded specimen used in this work was based on two considerations. In the first place such specimens are known to give relatively little scatter in fatigue test results and they are therefore convenient from the experimental point of view. Secondly, it is very difficult to avoid the use of non-load-carrying fillet welds in structural design and therefore the results obtained were likely to be of considerable use for design purposes.

The welded specimens were made using the SIGMA process. Owing to the high rate of deposition which this process involves it was not easy to obtain a uniform profile at the ends of the gussets. After some trials the method adopted, which produced the most uniform results, was to place short runs around the ends of the gussets first, filling in between these runs subsequently. In this way there were no stop/start positions in the area of fatigue crack initiation. All welds were made in the downhand position. The full welding sequence is shown in Fig.1b. Except where otherwise stated the welded specimens were aged at room temperature for 6 ± 1 weeks prior to testing.

3. METHOD OF TESTING

The majority of the constant amplitude fatigue tests were carried out in a 40 ton Losenhausen hydraulic testing machine at speeds between 333 and 1000 c/min. A small number of the constant amplitude tests were carried out in an Amsler Vibrophore at approximately 13000 c/min. The programmed tests were all carried out at testing speeds of from 333 to 666 c/min in a 40 ton Losenhausen machine which had been modified to permit it to be used for programmed tests.

The criterion of failure throughout the investigation was taken as complete rupture of the specimen.

The method of carrying out the programmed tests on the two materials was slightly different. In the case of the D74S material each test specimen in a particular series was tested with the same constant value of S_{min}. (the minimum stress in the cycle), only S_{max} being varied. However the tests on the H48 material were made in such a way that each series was tested at a particular stress ratio, S_{min}/S_{max}.

The constant amplitude tests were carried out in the same way as the programmed tests in order to provide data that was directly applicable to the analysis of the programmed test results. Thus the tests on D74S material were made such that S_{min} for each series was constant. The relevant values of S_{min} were chosen so as to give values of $\frac{S_{min}}{S_{max}}$ for failure at 2 x 10^6 cycles of approximately 0.5, 0 and -1. The resulting values of S_{min} were +2.5, 0 and -2.0 tonf/in^2 respectively for the notched specimens and +1.75, 0 and -1.25 tonf/in^2 for the welded specimens. The same values of S_{min} were used in the corresponding

programmed tests. However, for H48 material S-N curves were established with $\frac{S_{min}}{S_{max}} = R = +0.5, 0$ and -1.

The spectrum of stresses used for most of the programmed tests was based on a quadratic distribution similar to that used by Whitman and Alder [6]. However, in view of the rather low ratio of constant amplitude endurance limit stress to proof stress of the material, it was considered that loads which were only 10% of the maximum load might have a significant effect and the programme was modified to incorporate such loads. The quadratic distribution on which the spectrum was based was $n = 1.85\,(100 - L)^2$, where n is the number of cycles at L% of the maximum load. This distribution is shown in Fig. 2.

The basic programme (Programme 1) founded on this spectrum is shown in Fig.3. It was designed to introduce some degree of randomness into the order of application of the loads. It will be seen that in each programme block of 40000 cycles there were two peaks of 80% and three peaks of 'single' 100% loads. The load built up rapidly from 10% to the first 100% peak and fell rapidly to 10% from the third 100% peak, the other rises and falls occurring more slowly.

In the course of the investigation of the effect of the chronological sequence in which the loads were applied a number of variations of the basic programme were used and these are shown in Fig. 4. They were as follows:

Programme 2: This programme was essentially the same as Programme 1, in so far as each programme block contained 5 peaks, but the stress rose slowly to each peak and fell away rapidly.

Programme 3: For all practical purposes this programme is the same as Programme 2, but with the loads applied in the reverse order so that the stress rose rapidly to each peak and fell away slowly.

Programme 4: In this programme there was only one peak in each block, the stress rising directly from the 10% level to the 100% level without any intervening cycles and then fell away slowly from the peak. In order to keep the total number of cycles the same the peak consisted of three cycles at the 100% level.

Programme 5: This was identical to Programme 4, but in the reverse order, the stress rising slowly to the 100% level and then falling directly to the 10% level.

It should be noted that in each of these programmes the number of cycles at a particular stress level was the same. The reasons for the choice of these particular programmes are included in the general discussion of the test results.

In the work on H48 material all the tests were carried out at fixed values of stress ratio. As a result, some of the programmes representing a quadratic stress spectrum were, at first sight, of curious shape. For example Fig. 5a shows the original Programme 1 for half tensile loading. In addition some tests were carried out with programmes which were fundamentally different to that representing a quadratic spectrum. The first of these (Programme 6) represented

Level	No. of cycles in programme block
100%	2
90%	3
80%	5
70%	8
60%	15
50%	28
40%	64
30%	181
20%	768
10%	8915

a spectrum which was approximately parallel to the constant amplitude S-N curve. The programme was symmetrical about a single 100% peak and contained the following numbers of cycles at the various load levels. Each programme block contained approximately 10000 cycles.

This programme is not exactly parallel to the constant amplitude S-N curve owing both to limitations on the number of cycles which could be set on the testing machine and to the fact that the number of cycles at each stress level must be an integer. Thus, at the higher stresses, changes of one cycle have a larger percentage effect.

In Programme 7-10 one or two of these load levels were omitted as follows:

Programme 7 - 100% load level omitted
Programme 8 - 100% and 90% load levels omitted
Programme 9 - 10% load level omitted
Programme 10 - 10% and 20% load levels omitted

Also in the work on H48 material a randomised form of programme 1 was used. This programme (Programme 11) is illustrated in Fig. 5b. The degree of randomness was limited by the fact that the programme only allowed for 52 programme blocks. After some thought it was decided that the simplest way to produce a randomised programme was to write the details of each programme block from Programme 1 on a piece of paper and to draw these from a hat! The resulting programme is illustrated in Fig. 5b.

A typical strain record from a strain gauge mounted on a specimen is shown in Fig. 6. It shows part of programme 1, where the load is increasing rapidly from 10 to 100%. It will be noted that the 'single' 100% load has associated with it a number of smaller loads, the largest of which is somewhat less than 90%. These smaller loads have been ignored in the analysis of the results. It will also be seen that the blocks of constant amplitude stress were separated by periods during which the cyclic stress was maintained at a negligible level, these corresponding to the periods when the pulsator of the testing machine was moving to its new position for the next stress level.

4. TEST PROGRAMME

The following test programme was carried out:

4.1. D74S GB Material

a) Three constant amplitude S-N curves were obtained for notched specimens, the values of minimum stress for the three curves being -2, 0 and +2.5 tonf/in^2.

b) Three programmed load S-N curves were obtained for notched specimens, using the basic stress programme (Programme 1) at the same values of minimum stress as were used for the constant amplitude tests.

c) Three constant amplitude S-N curves were obtained for welded specimens, the minimum stress in this case being -1.25, 0 and -1.75 tonf/in^2.

d) Three programmed load S-N curves were obtained for the welded specimens using Programme 1 at the same values of minimum stress as were used in the constant amplitude tests.

e) In order to examine the effect of varying the order of the loads within the programme, tests were carried out on welded specimens using Programmes 2-5 with $S_{min} = 0$.

4.2. H48 material

a) Three constant amplitude S-N curves were obtained for welded specimens, the ratios $\frac{S_{min}}{S_{max}} = R$ being -1, 0 and + [illegible].

b) Two programmed load S-N curves were obtained for welded specimens with R = -1 and + 0.5 using Programme 1. In addition a small number of programmed tests were carried out on welded specimens using the same programme but with R = 0.

c) In order to study further the effect of varying the order of the loads within a programme, tests were carried out using a randomised programme (Programme 11) with R = 0.

d) In order to study the effect of the highest and lowest load levels, a programme based on a spectrum parallel to the constant amplitude S-N curve was used. The basic programme here (Programme 6) had 10 load levels from 10% to 100%. In other programmes some of these load levels were omitted. These were as follows:

Programme 7 - 100% load level omitted
Programme 8 - 100% and 90% load level omitted
Programme 9 - 10% load level omitted
Programme 10 - 10% and 20% load level omitted

5 CRACK PROPAGATION STUDIES

It was hoped that a study of the rates of growth of fatigue cracks under constant amplitude and programmed loading would throw further light on the problem. Such a study was carried out on a number of the specimens tested. The results of this study are described in detail in Appendix C.

6. RESULTS AND DISCUSSION

6.1. Constant amplitude tests on specimens of D74S material

The full results of the constant amplitude tests on the notched specimens are shown in the form of S-N curves in Fig. 7; the results for the welded specimens are shown in Fig. 8 and 9. All the diagrams are plotted in the form log S_R against log N, where S_R is the stress range (for the notched specimens the stress is given on the basis of gross cross-sectional area without deduction for the notch).

It will be seen from Fig. 7 that the tests on the notched specimens appeared to indicate a distinct 'fatigue limit', but the results of tests above that limit, and also those for the welded specimens, can be represented reasonably well by straight lines on the log S_R - log N plot. In order to make the best use of the results in the subsequent analysis of the results obtained under programmed loading, the best-fit straight lines were calculated by the method of least squares. These were as follows:

a) For notched specimens

$S_{min} = -2$ tonf/in^2, $\log S_R = 1.48 - 0.139 \log N$
$S_{min} = 0$, $\log S_R = 1.67 - 0.192 \log N$
$S_{min} = +2.5$ tonf/in^2, $\log S_R = 2.03 - 0.287 \log N$

b) For welded specimens

$S_{min} = -1.25$ tonf/in^2, $\log S_R = 2.18 - 0.283 \log N$
$S_{min} = 0$, $\log S_R = 2.14 - 0.281 \log N$
$S_{min} = +1.75$ tonf/in^2, $\log S_R = 2.16 - 0.304 \log N$

These lines give rise to the following fatigue strengths:

Type of specimen	Fatigue strength at 10^5 cycles, tonf/in^2	Fatigue strength at 2×10^6 cycles, tonf/in^2
Notched	- 2 to + 4.0	$\pm$ 2
	0 to + 5.1	0 to + 3.25
	+ 2.5 to + 6.4	+ 2.5 to + 5.0
Welded	- 1.25 to + 4.5	$\pm$ 1.25
	0 to + 5.4	0 to + 2.3
	+ 1.75 to + 6.1	+ 1.75 to + 3.5

The results for welded specimens agree well with other results reported in the literature [16, 17, 18].

The S-N curves show a number of interesting features. In the first place it will be seen that the slopes of the curves for the welded specimens are significantly steeper than the corresponding slopes for notched specimens. This fact is emphasised when the results are shown in the form of a Goodman diagram (Fig. 10). It will be seen that at 2×10^6 cycles the results for the notched specimens lie well above those for the welded specimens. However, at 10^5 cycles the results for notch and welded D74S lie very close to each other.

There is insufficient evidence to be able to define the precise reason for this behaviour since there are a considerable number of factors which are likely to have exerted some influence. These are:

a) The welded specimens contained tensile residual stresses in the region of the crack initiating notch (see Appendix B), whereas the notched specimens contained virtually no residual stresses. This would tend to make the welded specimens have a lower fatigue strength than the notched.

b) The stress concentration factor due to the notch was

probably higher than that caused by the welded joint. Work on similar steel specimens [9] has suggested that the S.C.F. for this type of welded joint is approximately 2.6 whereas the S.C.F. caused by the notch was approximately 4.5. Hence this factor would tend to make the fatigue strength of the welded specimen higher than that of the notched.
c) It is probable that the whole of the fatigue life of the welded specimens can be considered as consisting of crack propagation. This suggestion is also an extrapolation from findings made with steel specimens[10], in which it has been found that small crack like defects which act as fatigue crack initiators exist at the weld toe after welding. On the other hand the fatigue life of the notched specimens must have consisted of an initiation and a propagation period. Thus, as with a) above, at a given stress, the fatigue life of the notched specimens would be expected to be greater than that of the welded specimens.

This suggests that, at least under high stresses, which seems to be the condition required for the welded joints to have the higher fatigue strength, the magnitude of the stress concentration factor is the ruling factor. However under lower stresses this becomes of less importance, and the tensile residual stresses present in the welded joint and the necessity to initiate a crack in the notched specimen exert a greater influence.

A second feature of the results is the fact that mean stress has a greater influence on the fatigue strength of notched specimens than it does in the case of welded specimens. This can be seen by comparing the ratios of alternating and half tensile fatigue strengths (ranges) to pulsating tension fatigue strength (all at 2 x 10^6 cycles) for the two types of specimen. These are as follows:

	Notched	Welded
Half tensile fatigue strength / Pulsating tension fatigue strength	0.77	0.76
Alternating fatigue strength / Pulsating tension fatigue strength	1.23	1.09

This effect is almost certainly due to the presence of residual tensile stresses in the welded specimens so that, regardless of the stress ratio of the nominal applied stresses, the real stresses at the notch would have varied from an upper limit stress equal to the residual tensile stress. Hence a greater proportion of the applied stress range would have been fully tensile - and therefore more damaging - than in the case of notched specimens with no residual tensile stress.

As far as the apparent existence of a fatigue limit is concerned, it is interesting to consider this finding in the light of work which has been carried out elsewhere on non-propagating fatigue cracks. Re-analysis of results obtained by Frost et al, primarily under alternating loading, on a fracture mechanics basis [11] showed that, for all the materials which were tested (which did not include an aluminium-zinc-magnesium alloy), nonpropagating cracks would only form if $\frac{\Delta K}{E}$ was not greater than approximately 10^{-4} in$^{\frac{1}{2}}$, ΔK being the cyclic range of stress intensity factor calculated on the basis of the tensile part of the stress cycle.

If it is assumed that the notch used in the present work can be considered as a transverse slit of length 2a in a finite plate of width 2b, then the value of K is given [12] by:

$$K = \sigma (\pi a)^{\frac{1}{2}} \left[\frac{2b}{\pi a} \tan \frac{\pi a}{2b} \right]^{\frac{1}{2}}$$

where σ is the nominal applied stress. This formula does not include a plasticity correction factor, but since, in the regime of non-propagating cracks, the applied stress is small the error introduced by ignoring the plasticity correction will also be small. Inserting the values of a and b into this formula gives

$$K = 0.77\sigma$$

Hence, if $\frac{\Delta K}{E} = 10^{-4}$ in$^{\frac{1}{2}}$ and E = 4500 tons/in^2

$\Delta K = 0.45$ tons/in^2 $\sqrt{}$in.

$\therefore \Delta\sigma = 0.58$ tons/in^2 (semi stress range, alternating loading).

It will be noted that this is not in particularly good agreement with the results shown in Fig. 7. These indicate that the fatigue limit stresses were approximately 2.5 - 5.0 tons/in^2 under half tensile loading and 3.0 tons/in^2 under pulsating tension loading. No fatigue limit was established for the case where the minimum stress in the cycle was compressive, but it is certainly less than -2 to +1.5 tons/in^2. It therefore seems prudent to treat these results as dubious. Hence, in the analysis of the programmed test results the values of N taken from the constant amplitude S-N curves for low applied stresses were deduced by linear extrapolation of the straight line portions of the log S - log N plots (i.e. the possible existence of the fatigue limit was ignored). Since this extrapolation is in a region where N is large, the effect on $\Sigma\frac{n}{N}$ in the cumulative damage calculations is small.

The effect of ageing. As noted previously, most of the welded specimens were aged at room temperature for 6 ± 1 weeks prior to fatigue testing. However three specimens were naturally aged for different periods in order to determine whether the ageing period had a radical effect on fatigue strength, all being tested under a pulsating tension stress of 4 tons/in^2. Two of these specimens were aged for 8 days and gave endurances of 0.216 and 0.308 x 10^6 cycles and the third was aged for 120 days and gave an endurance of 0.217 x 10^6 cycles. All three results are shown in Fig. 8, from which it will be seen that they are in good agreement with the results for specimens aged for the normal period.

Some tests were also carried out on specimens which were artificially aged for 72 hours at 120°C, and these results are shown in Fig. 11. Also shown, for comparison, is the S-N curve for the naturally aged specimens taken from Fig. 8, and it is apparent that the results for the artificially aged specimens are in close agreement with it.

As a result of these tests it can be concluded that ageing has little effect on the fatigue performance of welded joints under low stresses (i.e. high cycle fatigue).

6.2. Programmed tests on specimens in D74S material

6.2.1. Tests using the basic programme (Programme1). The results of the programmed tests on notched and welded specimens are shown in detail in Tables 4 and 5 respectively. They are also shown in diagrammatic form in Fig. 12, 13 and 14, wherein $\log S_{Rmax}$ is plotted against $\log N$, S_{Rmax} being the stress range at the 100% load level and N being the total endurance under all stresses.

It is convenient to analyse the results by comparing them with Miner's linear cumulative damage rule. If the constant amplitude test results for a given type of detail and form of stress can be represented by a straight line on a $\log S_R$ - $\log N$ diagram, and if Miner's rule is assumed to apply, the programmed test results should also be represented by straight lines of the same slope as the constant amplitude lines. These theoretical straight lines are as follows:

Notched specimens

$S_{min} = -2$ tonf/in^2 $\log S_{Rmax} = 1.72 - 0.139 \log N$
$S_{min} = 0$ $\log S_{Rmax} = 1.96 - 0.192 \log N$
$S_{min} = +2.5$ tonf/in^2 $\log S_{Rmax} = 2.38 - 0.287 \log N$

Welded specimens

$S_{min} = -1.25$ tonf/in^2 $\log S_{Rmax} = 2.51 - 0.283 \log N$
$S_{min} = 0$ $\log S_{Rmax} = 2.48 - 0.281 \log N$
$S_{min} = +1.75$ tonf/in^2 $\log S_{Rmax} = 2.52 - 0.304 \log N$

These lines are plotted in Fig. 12, 13 and 14 for comparison with the test results. The distance parallel to the log N axis between a test result and the appropriate theoretical line is proportional to the value of the linear cumulative damage ratio $\Sigma\frac{n}{N}$. The values of this ratio for each specimen are also given in Tables 4 and 5. It should be noted that, in calculating these values, the values of N for stresses either above or below the limits of the experimental results were obtained by linear extrapolation of the $\log S_R$ - $\log N$ lines and the possible existence of a fatigue limit was ignored, as discussed previously. There is one obvious fallacy in this approach in that the lines representing the constant amplitude test results for notched specimens cross at approximately $S_R = 9$ tonf/in^2. This is obviously impossible and the curves must in fact merge gradually as the influence of minimum stress becomes less important with increasing stress range. However examination of the values of $\frac{n}{N}$ in the Tables shows that the major contributions to the values of $\Sigma\frac{n}{N}$ come from stresses either within or only slightly outside the range covered by the constant amplitude results. It is therefore unlikely that the extrapolation caused any significant error.

The results themselves show a number of interesting features. In the first place, only one specimen gave a value of $\Sigma\frac{n}{N}$ which was less than unity, this being notched specimen PNA/3 which was tested under an upper limit stress range varying between -2 and +4.7 tonf/in^2 and gave $\Sigma\frac{n}{N} = 0.84$. The remainder of the notched specimens gave values of $\Sigma\frac{n}{N}$ ranging between 1.58 and 14.84, while for the welded specimens $\Sigma\frac{n}{N}$ varied between 2.60 and 7.51.

For the notched specimens the values of $\Sigma\frac{n}{N}$ appear to be strongly dependent on the applied stress; as can be seen from Fig. 12 the divergence between the experimental results and the relevant theoretical Miner line increases rapidly with increasing stress. Thus, considering the tests carried out with $S_{min} = 0$, the results are well represented by the line:

$$\log S_{Rmax} = 2.87 - 0.33 \log N$$

for which the slope of -0.33 can be compared with the corresponding slope of -0.19 for constant amplitude tests. The apparent dependence of $\Sigma\frac{n}{N}$ on S_{Rmax} for all three test series is shown in Fig. 15.

For the welded specimens, however, the values of $\Sigma\frac{n}{N}$ appeared to be largely independent of the value of S_{Rmax} and a diagram of the form shown in Fig. 15 merely reflected the scatter in the value of $\Sigma\frac{n}{N}$. The average values of $\Sigma\frac{n}{N}$ were 4.42 for specimens tested with $S_{min} = 1.25$ tons/in^2, 4.39 for tests with $S_{min} = 0$ and 5.30 for tests with $S_{min} = +1.75$ tons/in^2, the overall average being 4.59. As can be seen from Fig. 13 and 14, the test results were closer to being parallel to the Miner line than was the case with the notched specimens. For the tests carried out with $S_{min} = 0$ the best fit straight line is:

$$\log S_{R\,max} = 2.42 - 0.241 \log N$$

where the slope of -0.24 can be compared with -0.28 for the constant amplitude results. (Note that the corresponding slopes for notched specimens were - 0.33 and - 0.19). On the basis of the results shown in Fig. 13, it could in fact be argued that the slope of the line representing the programmed test results with S_{min} 0 was even closer to that of the constant amplitude results, since the two results obtained at stresses of 5.5 and 6.2 tons/in^2 could be considered to be the start of a 'knee' formation as a result of the 10% load becoming too small to have any effect. In the meantime, however, it has been assumed that all the experimental

points are relevant to the linear relationship stated above.

A particularly interesting feature is the very large number of specimens, both notched and welded, which gave individual values of $\frac{n}{N}$ at a particular stress level which were greater than unity. In fact this occurred in 5 of the 11 notched specimens and in 21 of the 23 welded specimens tested in this stage of the investigation. It is notable that, in the case of the notched specimens, the occurrence of values of $\frac{n}{N}$ greater than unity was restricted to specimens tested with maximum stress ranges of at least 9.5 tons/in^2, this reflecting the fact, - noted above, - that $\Sigma \frac{n}{N}$ tended to increase as applied stress increased. The highest value of $\frac{n}{N}$ recorded for an individual stress level was 5.004 at the 80% level in notched specimen PNA/1. However in all except two specimens the greatest value of $\frac{n}{N}$ was associated with the 70% load level. This means that, even if damage at all other stress levels is ignored, the cycles at 70% of the maximum stress did less fatigue damage in the programmed tests than in constant amplitude tests. Much the most likely explanation for this behaviour is that the very small number of cycles at high stress introduced favourable residual compressive stresses around the propagating crack, whose effects far outweighed the small contribution which such stresses made to the propagation of the crack. A second possibility is that the large number of cycles at low stress had a coaxing effect, but this seems unlikely in view of the relatively poor performance of the notched specimens tested at the lower applied stress.

It has been suggested extraneously that stresses less than about 80% of the endurance limit make a negligible contribution to damage in programmed tests. If this were so a flattening off of the log S_{Rmax} - log N lines would be expected at low stress levels, when the 10% stress level ceased to contribute to fatigue damage, since 40% of the cycles in the programme are at the 10% level. As already noted, it could be argued that there is some indication of the formation of a 'knee' in the curve for welded specimens tested with $S_{min} = 0$, but no 'knee' is apparent in any of the other curves. Even for the welded specimens it must be realised that the 10% stress levels of the two specimens which may be on the knee were only about 0.6 tonf/in^2, whereas the constant amplitude fatigue limit appeared to be at about 1.5 tonf/in^2.

In order to investigate the effects of stresses well below the fatigue limit two specimens were tested in which the 10% level was omitted. Apart from omitting this level, the remainder of the programme was identical to the original Programme 1. The results for these specimens are given in Table 6 and they are also shown in Fig. 16.

The mean value of $\Sigma \frac{n}{N}$ for these two specimens was approximately 4.2 which is almost the same as the mean of the results for the basic programme. The actual lives for these specimens can be compared directly with those of the earlier tests if they are multiplied by a factor of

$$\frac{40000}{40000 - 16806} - 1.73,$$

there being a total of 40000 cycles in the original programme and 16806 cycles at the 10% level. Multiplication by this factor gives equivalent lives of 4.92×10^6 for specimen PW/13 and 6.74×10^6 for specimen PW/14. These results are also plotted in Fig. 16, where they may be compared with the line for the original tests. It will be seen that they lie close to this line, as would be expected from the similarity between the values of $\Sigma \frac{n}{N}$. It would therefore appear that in these specimens the 10% stress level had very little effect. This result was not expected and does not throw light on the reason for the continuation of the log S_{Rmax} - log N curve at the same slope at low stress levels.

6.2.2. Tests using other programmes. The objective of this part of the investigation was to determine the effect of varying the order of application of loads within a programme block, while at the same time keeping the total number of cycles within each programme block at each stress level the same. As a result of determining the effect of ordering it was hoped to define the programme giving the minimum life in order to test the degree of safety or risk in employing the linear cumulative damage rule. Before considering the test results obtained it is convenient to outline the information which has been obtained in other investigations.

As was noted in the introduction to this report, much of the work on cumulative fatigue damage has involved simple two level tests on plain and notched specimens and this has indicated that the order in which the stresses are applied has a significant effect on the fatigue life. In general, rotating bending tests on unnotched specimens of steels and aluminium alloys have given values of $\Sigma \frac{n}{N}$ which were greater than 1.0 if the lower stress was applied first but less than 1.0 is the upper stress was applied first. On the other hand, under axial loading $\Sigma \frac{n}{N}$ has usually been greater when the higher stress has been applied before, rather than after, the lower stress, and this has been found to be true both for plain and notched specimens.

It seems almost certain that this effect is related to the influence of residual stresses. It has been shown in several investigations that the application of a single cycle of high tensile stress (prior overloading) before subsequent fatigue testing at a lower stress can result in a large increase in life by introducing compressive residual stresses at the notch. There is no reason why the same mechanism should not operate in axial two step high-low fatigue tests. It does not operate in rotating bending tests because, at the moment immediately prior to the change to the lower stress level, only one half of the specimen will be preloaded in the right sense. The region subjected to the final high

compressive stress will, if a crack is present, be left in a state of residual tension so that, under subsequent nominally alternating stresses, the life will be reduced rather than increased.

The information available on the effect of varying the order of stresses in a spectrum is, however, very limited. Nevertheless an effect due to ordering has been found. For example Schijve and Jacobs [13], in axial loading tests on rivetted sheet specimens of 2024 and 7075 aluminium alloys, found that a rapid rise/slow fall programme gave a low life, a slow rise/slow fall programme a medium life and a slow rise/rapid fall programme a long life. It was thought that the compressive residual stresses introduced by the 100% load level in the slow rise/rapid fall case were such that the low stresses which follow this level are more or less ineffective. However in the rapid rise/slow fall case each following load level is only slightly lower than the preceding one, so that there is more chance of the residual stresses being relaxed by plastic deformation or by crack propagation. The results for alloy 7075 showed that the effect of ordering was much less marked than in the case of 2024 and this was thought to be due to the relatively high proof stress of this material and also to the fact that the test stresses were lower for this alloy than for alloy 2024. Residual stresses therefore played a much less significant part. Tests showing the opposite effect of ordering have been reported by Hardrath, Naumann and Guthrie [14,15] - i.e. the rapid rise/slow fall programme giving a high life, slow rise/slow fall a medium life, and slow rise/rapid fall a low life. In these tests the effect was quite marked for both alloys 7075 and 2024. The reason for this difference in behaviour is not clear. The American tests differ from those carried out in Holland in that the maximum stresses used had a considerably higher ratio to the proof stress.

In the current work four main variants of the basic programme were used, as indicated previously in the section entitled 'Methods of Testing', and details of them are shown in Fig. 4.

Programmes 2 and 3 were similar to Programme 1 in so far as each programme block contained five peaks. However, whereas in Programme 1 the arrangement of cycle blocks was symmetrical in Programme 2 the stress rose rapidly to each peak and fell away slowly and in Programme 3 the stress rose slowly and fell away rapidly. The results of the fatigue tests using Programme 2 and 3 are given in detail in Tables 7 and 8 respectively and are shown in Fig. 16, in which is also shown the S-N curve relating to results obtained with the basic programme. It will be seen that, although programme 3 gave slightly longer lives than Programme 2, there was extremely little difference between them and both gave slightly longer lives than the basic programme. This is reflected in the average values of $\Sigma\frac{n}{N}$, which were 5.75 for Programme 2 and 6.58 for Programme 3 compared with 4.3 for the basic programme.

In Programme 4 and 5 there was only one peak per programme block. In Programme 4 the stress rose directly from the 10 to 100% level without any intervening cycles and then fell away slowly from the peak. In Programme 5 the stress rose slowly to the peak and then fell vertically to the 10% level. The results obtained with these two programmes are given in detail in Tables 9 and 10 and are also shown diagrammatically in Fig. 16. Since only two tests were carried out using Programme 4 it is not possible to draw any valid conclusions about its effect, although the lives were obviously very similar to those obtained with the other programmes. The tests with Programme 5, however, do show a distinct tendency for $\Sigma\frac{n}{N}$ to increase as the stress decreases, and on the basis of a single test result there is some indication of the formation of a knee at a maximum stress range in the spectrum of about 7.5 tonf/in^2.

This behaviour is consistent with the hypothesis that the effect of ordering loads within a programme results from the introduction of compressive residual stresses at the notch on the application and removal of high loads. In Programme 5, as the nominal stress decreases the high loads will still be sufficient to cause yielding at the notch with the consequent introduction of residual compressive stresses, but the lowest loads (which immediately follow the high load) are then so small that they merely result in an actual (as opposed to a nominal) stress range which is purely compressive in nature (i.e. varying upwards from the residual compressive stress). Thus as the nominal stress in the spectrum is decreased the lowest loads become less damaging and $\Sigma\frac{n}{N}$ would be expected to increase.

It seems probable that the effect would be somewhat more marked - i.e. $\Sigma\frac{n}{N}$ would be slightly greater - if, instead of each programme block containing only one peak with the 3 high loads applied consecutively, it were to contain three separate peaks with a vertical fall after each. In this way the compressive residual stress would be re-established more frequently.

The reason why Programme 2 (slow rise/rapid fall with 5 peaks) did not show the same behaviour as Programme 5 is probably that, in Programme 2, the fall was not vertical. Hence the successively decreasing stresses, although only applied for a relatively small number of cycles, were sufficient to propagate the crack out of the residual stress region generated by the highest stresses so that virtually all the cycles in the programme were damaging.

By the same token it was anticipated that the rapid rise/slow fall Programme 3 would tend to give a lower value of $\Sigma\frac{n}{N}$ than the basic programme and that Programme 4 (vertical rise/slow fall) would give the lowest value of all since the cycles at each stress level would have the maximum opportunity to break through the compressive residual stress barrier created by the previous higher loads. In fact the results for Programme 3 did not bear out this prediction and, as noted previously, insufficient specimens were tested under Programme 4 to enable any conclusions to be drawn. It is interesting to note, however,

the relatively low value of $\Sigma\frac{n}{N}$ (= 4.88) obtained with the specimen tested at $S_{R_{max}}$ = 6.9 tonf/in^2 using Programme 4.

In general, however, it must be concluded that the order of application of loads in the spectrum only has a small effect in fillet welded joints of D74S. The results for Programme 5 suggest that it may be possible to obtain abnormally high values of $\Sigma\frac{n}{N}$ if the order of load application is suitable, but such a spectrum would be most unlikely to exist in service.

6.3. Constant amplitude tests on specimens of H48 material

Although it was not considered that the H48 material would behave very differently from D74S under fatigue loading, it was thought wise to carry out confirmatory constant amplitude tests. These were restricted to welded specimens, the specimen design used being the same as in the earlier work, as shown in Fig. 1b. Since it had been decided to study the effect of programmes in which R = S_{min}/S_{max} = +0.5 and -1 throughout the programme, constant amplitude tests with these values of R were carried out in addition to those in which R = 0. It will be recalled that in the tests on welded specimens of D74S material the three S-N curves had constant values of S_{min}, namely + 1.75, 0 and -1.25 tons/in^2 respectively, rather than constant values of S_{min}/S_{max}. Hence only the results obtained under pulsating tension loading can be compared directly between the two material.

The results of all these tests are plotted in Fig. 17 and 18 in the form log S_R against log N. It will be noted that when presented in this form variations in the value of R have little effect on endurance.

The results of these tests were analysed by means of a regression analysis which gave the following as the best fit straight lines in the log S_R versus log N plot:

for R = -1, log S_R = 2.68 - 0.358 log N
for R = 0, log S_R = 2.54 - 0.359 log N
for R = +0.5, log S_R = 2.12 - 0.277 log N

The first point to note is the remarkable similarity between the regression lines for R = -1 and 0. The slopes are practically identical, the position of the line for R = -1 being shifted to somewhat higher stress (range) levels for a given life.

Secondly it will be seen that the line for R = +0.5 crosses that for R = 0. It seems unlikely that this is a representation of the true state of affairs and it is felt that it probably be attributed to scatter, although the tests at low stress ranges for R = +0.5 seem to have given consistently high endurances. At the low cycle end of the S-N curve results for R = +0.5 would be expected to show lower endurances than for R = 0 since in this case the upper limit stress will be closer to the tensile strength of the material. The effect would be expected to be less marked at high endurances (low stress range) and in this region the stress range itself might be assumed to be the governing factor. It may therefore be that the results in the high endurance range all come from a single family.

In spite of these considerations it is proposed that $\Sigma\frac{n}{N}$ should be calculated on the basis of the regression lines given since these must be taken to be the best representation of the available experimental evidence in the absence of other data.

It is also interesting to compare the line for R = 0 for H48 material with that for D74S material, for which the regression line was:

$$\log S_R = 2.14 - 0.28 \log N$$

This also crosses the R = 0 line for H48 and is almost coincident with the R = +0.5 line for the latter material.

D74S has a lower 0.2% proof strength than H48 so that one might expect it to give lower endurances in the low cycle region when the stress range approaches the proof strength.

The above lines give rise to the following fatigue strengths for welded H48 material.

Fatigue strength at 10^5 cycles, tonf/in^2	Fatigue strength at 2 x 10^6 cycles, tonf/in^2
$\pm$ 3.9	$\pm$ 1.3
0 to 5.6	0 to 1.9
5.5 to 11	2.3 to 4.6

These results are plotted in the modified Goodman diagram, Fig. 10, where they may be compared with the D74S results.

6.4. Programmed load tests on specimens of H48 material.

6.4.1. Original programme (Programme 1) S_{min} = 0. In order to provide a further check that the introduction of a new material did not invalidate earlier work, three specimens were tested using the original programme (Programme 1) and with R = 0.

The results of these tests are given in Table 11. These results are plotted in the form log $S_{R_{max}}$ - log N in Fig. 19, on which is also plotted the scatter band for tests on D74S material using the same programme. It will be noted that the results for H48 material fall near the centre of this scatter band and are therefore in good agreement with the earlier tests.

6.4.2. Original programme (Programme 1) S_{min} = 0.5 S_{max}

Tests were carried out using the original programme (Programme 1) for the stress range, but with the value of S_{min} in each block equal to half the value of S_{max} in that block (Fig. 5a). The results of these tests are given in Table 12.

These results are plotted in the form log $S_{R_{max}}$ - log N in Fig. 20. In this figure the regression line calculated from the results is plotted and it may be compared with the line calculated on the basis of Miner's hypothesis.

These lines are respectively:

$\log S_{Rmax} - 2.48 - 0.274 \log N$ (Regression line)
and $\log S_{Rmax} = 2.44 - 0.277 \log N$ (Miner line)

Clearly the results of the tests are in fairly close agreement with this hypothesis. The equations and the figure show that the lines are very nearly parallel, the actual results being displaced slightly towards higher lives. The mean value of $\Sigma \frac{n}{N}$, which was 1.8, is considerably lower than the values of about 4 found for R = 0. Furthermore there was one specimen for which $\Sigma \frac{n}{N}$ was approximately 0.5, although this is based on a value of N found by extrapolation of the constant amplitude S-N curve (Fig. 18). These results therefore suggest that for fluctuating stresses Miner's hypothesis is less conservative than it is for R = 0.

The results were analysed above on the basis of a best fit straight line. However an inspection of Fig. 20 suggests that they may be better represented by a curve (chain dotted in the figure). Certainly a flattening off of the curve at high values of S_{Rmax} might be expected, since when S_{Rmax} - 12 tonf/in^2, for example, the maximum stress applied is 24 tonf/in^2 which approaches the proof stress of the material. For S_{Rmax} = 16 tonf/in^2 the life would be $\frac{1}{4}$ cycle since 32 tonf/in^2 exceeds the tensile strength of the material. When seen from this point of view, the low values of $\Sigma\frac{n}{N}$ at high stress ranges are not surprising.

6.4.3. Original programme (Programme 1), Smin = - Smax

Tests were also carried out with R = -1, using once more the original programme. The results of these tests are given in Table 13.

These results are plotted in the form S_{Rmax} - log N in Fig. 21. In this figure the regression line and the theoretical line based on Miner's law are plotted as before. The equations of these lines are:

$\log S_{Rmax} = 3.61 - 0.436 \log N$ (Regression line)
$\log S_{Rmax} = 3.04 - 0.358 \log N$ (Miner line)

In this case the results do not lie paralle to the Miner line; but they are all above it. Since the results are not parallel to the Miner line, the mean value of $\Sigma\frac{n}{N}$ over the whole range of stresses is meaningless. The mean value varies with stress. At S_{Rmax} = 15 ton'/in^2 the mean value of $\Sigma \frac{n}{N}$ = 2.36 and at S_{Rmax} = 5 tonf/in^2 the mean value of $\Sigma \frac{n}{N}$ = 1.34. Both these values are considerably less than the value of about 4 found for R = 0. We therefore have the rather strange fact that both for R = +0.5 and R = -1 the value of $\Sigma\frac{n}{N}$ is less than that for R = 0.

The effect of variations in the value of R may be shown by plotting the results in the form of a modified Goodman diagram (see Fig. 22). In this figure the values plotted are the values of S_{max} and S_{min} appropriate to the 100% stress range level which gave failure within the given number of cycles. As is normally found for constant amplitude tests on as welded (not stress relieved) specimens, the curves for 2 x 10^6 and 6 x 10^5 cycles are virtually parallel to the line for R = 1. This fact results from the presence of residual stresses. However at low endurances residual stresses have less effect and this is shown up by the tendency to diverge from parallelism for negative values of R shown by the curve for 10^5 cycles. This part of the curve is not shown as a solid line since the result on it for R = -1 was obtained by extrapolation and is not directly confirmed by the experimental data.

6.4.4. Randomised programme R = 0. It was considered that the way in which the load levels were ordered might well contribute to the high values of $\Sigma \frac{n}{N}$ which were found. It was therefore decided to carry out tests using a programme having the same number of cycles at each load level as programme 1; but one in which the order of application was quite random. This was Programme 11. The results of tests using this programme are given in Table 14.

These results are plotted in the form $\log S_{Rmax}$ - log N in Fig. 23. The regression and the Miner's law lines calculated for this series were as follows:

$\log S_{Rmax} = 3.04 - 0.348 \log N$ (Regression line)
$\log S_{Rmax} = 2.90 - 0.359 \log N$ (Miner's law)

The results are seen to be very nearly parallel to the theoretical line. The mean value of $\Sigma \frac{n}{N}$ can therefore be calculated and was 3.6. This agrees reasonably with the values obtained previously for D74S material using an ordered programme. It can therefore be assumed that the effect of random ordering is negligible. The results of these tests may be compared in the figures with the scatter band for D74S material obtained using Programme 1. It will be seen that the constant amplitude behaviour is reflected here in that at low stress ranges the H48 material gives lower lives than the D74S material, while the reverse tends to be true at high stress ranges.

6.4.5. Tests using programmes parallel to the constant amplitude S-N curve. In an attempt to explore further the reasons for the high values of $\Sigma \frac{n}{N}$ obtained using Programme 1, it was decided to carry out tests using a programme parallel to the constant amplitude S-N curve, i.e. one in which the number of cycles at any load level was proportional to the number of cycles required to cause failure in a constant amplitude test at that load level.

Two important factors in cumulative damage fatigue tests are the effects of both the highest and the lowest stress levels in the programme. It has been suggested that high values of $\Sigma \frac{n}{N}$ result either from beneficial residual stresses introduced by the former or from coaxing as a result of the latter. Studies of the effect of the extreme stress levels in Programme 1 were hampered by the fact that neither contributed more than about 0.3% to the value of

$\Sigma\frac{n}{N}$. The greatest contribution to this sum came from the 70% level followed by the 50% and 80% levels, these three providing some 80% of the total. It was decided that this difficulty could be overcome by using a spectrum parallel to the S-N curve in which each stress level would contribute equally to the value of $\Sigma\frac{n}{N}$. Unfortunately at the time that these programmed tests were started all the constant amplitube data for H48 material was not available. The spectrum used was parallel to the constant amplitude curve for D74S.

For a typical specimen, assuming a total life such that $\Sigma\frac{n}{N} = 1$, values of $\frac{n}{N}$ at each stress level may be calculated, firstly where N is the life determined from the D74S constant amplitude results and secondly where it is based on the H48 results. These were as follows:

Stress level	$\frac{n}{N}$(based on D74S)	$\frac{n}{N}$ (based on H48)
100%	0.084	0.038
90%	0.087	0.043
80%	0.096	0.048
70%	0.095	0.056
60%	0.104	0.074
50%	0.102	0.077
40%	0.106	0.095
30%	0.108	0.120
20%	0.109	0.172
10%	0.109	0.277
	1.000	1.000

It will be noted that the values of $\frac{n}{N}$ remain sensibly constant when based on the D74S results but differ quite markedly when based on the H48 data. The results quoted are all based on the latter.

The results for Programmes 6, 7, 8, 9 and 10 are all given in Table 15 and are plotted in Fig. 24. The purpose of these tests was to study the effect of the absence of the highest and lowest load levels on the endurances. In order to make any meaningful comparison, it is necessary in this instance to give the endurance in terms of the total number of programmes survived rather than the total number of cycles. Furthermore the values of stress given in the table and plotted in the figure are those for the 100% stress level although in Programme 7 and 8 this stress level was absent.

Figure 24 shows considerable scatter for all the programmes, but, in spite of this, it is possible to draw some conclusions from the results. First of all, it is quite clear that the omission of the two lowest levels (Programme 10) brings about a noticeable reduction in the number of programmes endured. The omission of the top two levels (Programme 8) would also seem to reduce the number of programmes survived, but to a much less marked degree. With ten stress levels in the programme (Programme 6) a high value of $\Sigma\frac{n}{N}$ ($\approx$ 3.5) was obtained. In a programme with only one stress level (i.e. a constant amplitude test) obviously $\Sigma\frac{n}{N}$ would be equal to 1. This suggests that a reduction in the number of stress levels from either the top or the bottom of the programme should lead to a reduction in life. This is borne out by the present results, but it is interesting that the effect of the removal of the two lower levels is so much more marked than that of the removal of the two upper levels. This result would seem to suggest that it could be coaxing which is responsible for the high values of $\Sigma\frac{n}{N}$ and not the introduction of favourable residual stresses by the 100% load level.

It is interesting to note that specimens 2/PW10/1-4 are the first welded specimens in the whole of the testing programme for which a value of $\Sigma\frac{n}{N} < 1$ has been recorded, with the one other exception of specimen 2/PWT/2. Programmes 6, 7 and 8, all with a completely different spectrum to the quadratic distribution used in the original work, produced consistently high values of $\Sigma\frac{n}{N}$.

CONCLUSIONS

1. In the high cycle range welded joints in high strength Al:Zn:Mg alloys have similar fatigue properties to the same joints in lower strength aluminium alloys.
2. Nevertheless, the ability of such alloys to carry occasional stresses which would be above the static allowable stress for lower strength materials, means that under variable amplitude loading they can be employed with benefit.
3. The work has shown that in variable amplitude tests using a programme based on a quadratic spectrum the Miner hypothesis underestimates the life of welded joints. For R = 0 values of $\Sigma\frac{n}{N}$ of approximately 4 were obtained.
4. It was impossible, by changing the ordering of the programme blocks, to produce any significant variation in the value of $\Sigma\frac{n}{N}$.
5. However, changes in the value of R either in the positive or negative direction did cause reductions in the value of $\Sigma\frac{n}{N}$. However, mean values of $\Sigma\frac{n}{N}$ were still greater than unity. Only one welded specimen tested using the quadratic spectrum gave a value of $\Sigma\frac{n}{N}$ of less than one. This spectrum was tested with R = 0.5.
6. For welded specimens the value of $\Sigma\frac{n}{N}$ was reasonably independent of stress. This was not the case for notched specimens for which high stress ranges gave high values of $\Sigma\frac{n}{N}$ (up to approximately 15) whereas low stress ranges

gave low values (as low as approximately 0.8)
7. Tests carried out using a completely different spectrum parallel to the constant amplitude S-N curve also gave consistently high values of $\Sigma\frac{n}{N}$. These tests were carried out to study the effects of the lowest and highest stress ranges in the programme. Omission of either of these brought about reductions in the value of $\Sigma\frac{n}{N}$ but the reduction caused by omitting the lowest stress levels was the greatest. In this case values of $\Sigma\frac{n}{N}$ of less than unity were obtained. This suggests that the high values of $\Sigma\frac{n}{N}$ obtained may be due to coaxing.

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APPENDIX 'A'

TESTS TO DETERMINE THE INFLUENCE OF TEEPOL

In some of the early tests the onset of fatigue cracking was, on occasions, detected by the use of Teepol. When the susceptibility of the aluminium-zinc-magnesium alloy D74S to stress corrosion cracking was realised, it was thought that the use of this substance could have had a deleterious effect in those tests in which it was used. It was therefore decided to investigate this possibility.

This was achieved by carrying out fatigue tests on welded specimens fabricated from D74S material, the form of the specimens being identical to that used in the main testing programme (Fig. 1b). The tests were made under programmed loading using Programme 1 (Fig. 3) with lower limit stress equal to zero.

Environment	Max. stress, S_R max., tonf/in^2	Cycles to failure, N	Corrected life for S_R max = 11 tonf/in^2, N_c	Log mean value of N_c
Air	11.0	719,370	719,370	696,900
	11.9	511,160	675,300	
Dry Air	11.0	440,000	440,000	
	11.0	759,980	759,980	684,500
	11.3	580,190	639,300	
	11.1	999,380	1,030,000	
Teepol Drip	12.1	156,350	218,900	
	11.0	199,270	199,270	209,100
	11.9	159,770	209,800	

Two specimens were tested in air, four specimens were tested with the weld areas sealed in a polythene bag containing silica gel and three were tested with a continuous drip of Teepol onto the weld areas. The drip consisted of a mixture of 25% Teepol and 75% tap water.

These tests were all carried out with S_R max., the maximum stress range in the programme, approximately equal to 11 tonf/in^2. In order to be able to compare the results a corrected value of N, N_c, was calculated for those specimens for which S_R max. differed from 11 tonf/in^2. This corrected value was calculated from the known slope of the original log S_R max. - log N curve. For each environment the log mean value of N_c then was calculated.

A summary of the results obtained is shown in the following table. It will be seen that whether or not the air was dry made little difference to the value of the mean endurance but that the continuous drip of Teepol brought about a very marked reduction in life.

The results are plotted in the form of an S-N diagram in Fig. A1. Clearly Teepol applied continuously from the start of a test brought about a marked decrease in life. The results of the tests in air may be compared with those of the original tests. In the original tests, Teepol was used on some specimens, but by no means all, and when it was used it was not applied until a number of cycles such as would be likely to have caused crack initiation had elapsed. Although, with one exception, the results for tests in air lie above the best fit straight line from the original results, so in this region of the curve do the original results themselves. Indeed it was at one time suggested that those results might have been better represented by a curve. Only one of the present results lies well above the scatter band of the original tests.

CONCLUSION

Clearly it was wrong to use Teepol as a method of detecting fatigue crack initiation in this material. However, the results do not appear to have been seriously affected by its use for two reasons:

a) It was not used on all the original specimens.
b) It was not used until a considerable portion of the life had expired.

It seems likely that the main effect of a continuous Teepol drip is to accelerate fatigue crack initiation and that its effect on crack propagation is less significant.

APPENDIX 'B'

RESIDUAL STRESS MEASUREMENTS

Residual stress measurements were made by the relaxation method using a mechanical gauge measuring between balls hammered into the surface of the specimen. The gauge length was 20 mm. The two specimens used for these measurements were identical to those used in the fatigue investigation. The layout of the gauge lengths is shown in Fig. 2. This layout of gauge lengths enabled strains to be measured in the transverse and longitudinal directions. Measurements were made both after welding and after natural ageing. No detectable change had occurred during the ageing period. The specimens were then slit along the lines shown in Fig. B1 to relieve the stresses and measurements of the resulting strains were made.

The results of the residual stress measurements are shown in Fig. B2. It will be seen from this diagram that the two specimens tested produced very similar results. The mean of the values for the two specimens of the compressive strain measured near the edge of the plate was $2,400 \times 10^{-6}$ in/in, equivalent to a stress of 10.5 tons/in^2. The mean longitudinal tensile strain measured near the edge of the weld was $1,000 \times 10^{-6}$ in/in indicating a stress of 4.5 tons/in^2. If we assume that this stress acts throughout the weld and throughout the plate in the vicinity of the weld and also that approximately half of the tensile force in the weld is balanced by compression in the gussets we find a close agreement between the sums of the tensile and compressive forces. This roughly confirms our assumption of the magnitude of the residual stress in the weld. Further confirmation of this comes from work carried out for MEXE under another contract on the welding of aluminium-zinc-magnesium alloys of medium strength. Extrapolation from results reported in the fifth progress report of that contract (C48/PR5) indicate that the proof stress in the heat affected zone immediately after welding might be of the order of 4-5 tons/in^2.

APPENDIX 'C'

FATIGUE CRACK PROPAGATION IN Al:Zn:Mg ALLOY

1. INTRODUCTION

The process of fatigue failure in a structural component may be split up into three stages. These are (a) crack initiation, (b) crack propagation and (c) final rupture, which occurs when the residual material cross section is insufficient to carry the applied load. In the case of a welded component crack initiation occupies only a small proportion of the life, the remainder being propagation.

Signes et al C1 showed that very sharp slag intrusions comparable with cracks, may remain after welding in the region close to the weld which did not melt completely during welding. Although these findings were confined to steels, it seems likely that similar defects will be present in welded aluminium alloy. Assuming that this is true it can be taken that cracks or crack-like defects are already present near to welds before any loading is applied, so that the initiation stage effectively does not exist and the whole test is concerned with crack propagation.

Therefore as an extension to the work on fatigue testing of welded and notched Al:Zn:Mg alloy specimens, rates of fatigue crack propagation in this material were studied. This was done by observing the fatigue crack when it was propagating across the plate, having, in the case of the welded specimens, first propagated through the thickness of the plate.

Fatigue crack propagation was also studied using fractographic techniques. In this way the appearance of the fracture surfaces of a specimen was related to the load spectrum that had been applied to the specimen.

The data obtained was analysed on a fracture mechanics basis.

2. CRACK PROPAGATION STUDIES

2.1. Specimen design and testing details

The specimens have been described in the main report. Both notched and welded specimens were used in the crack propagation studies, tested under either constant amplitude loads or block programmes of loading. The rate of crack propagation was measured using the wire grid technique. The grids were attached to the plate in the regions which the cracks were expected to traverse, and as the crack grew it caused the wires on the grid to break. As the wires broke a record was automatically obtained of the number of cycles undergone by the specimen. The wires were spaced at 1/10 in. intervals for a distance of 1 in. Figures C1 and C2 show the positions at which the grids were fixed, for the welded and notched specimens respectively. Since the crack propagation work was carried out on specimens already being tested for obtaining fatigue life data the loading conditions were identical with those already described in the report.

2.2. Results.

For each specimen four sets of crack propagation results were obtained, from the four grids covering the fracture

TABLE 5. (Continued).

Specimen no.	Failure at:		Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma \frac{n}{N}$	Total cycles $\times 10^6$
	Stage no.	Load level						
c) - S min = +1.75								
PWT/1	12	90%	14.0	19	2 230	0.009		
			12.6	2 546	3 160	0.806		
			11.2	7 250	4 660	1.555		
			9.8	18 710	7 230	2.587	7.51	0.248
			7.0	41 760	21 900	1.907		
			4.2	72 980	117 000	0.624		
			1.4	104 800	4.35×10^6	0.024		
PWT/2	34	90%	12.0	17	3 710	0.004		
			10.8	2 534	5 250	0.483		
			9.6	6 750	7 730	0.873		
			8.4	17 090	12 000	1.424	4.18	0.224
			6.0	37 720	36 300	1.039		
			3.6	66 930	195 000	0.343		
			1.2	92 850	7.23×10^6	0.013		
PWT/3	22	90%	10.25	34	6 230	0.005		
			9.2	4 820	8 890	0.542		
			8.2	13 410	13 000	1.031		
			7.2	24 290	19 900	1.723	4.98	0.456
			5.1	76 620	61 900	1.238		
			3.1	135 500	318 000	0.426		
			1.0	191 300	1.32×10^7	0.014		
PWT/4	24	90%	8.0	83	14 100	0.006		
			7.2	11 661	19 900	0.586		
			6.4	32 060	29 300	1.094		
			5.6	82 000	45 500	1.802	5.28	1.114
			4.0	183 900	138 000	1.332		
			2.4	326 000	739 000	0.441		
			0.8	460 200	2.74×10^7	0.014		
PWT/5	12	90%	6.0	184	36 300	0.005		
			5.4	25 951	51 300	0.506		
			4.8	71 380	75 600	0.944		
			4.2	182 700	117 000	1.562	4.57	2.448
			3.0	410 500	355 000	1.156		
			1.8	728 000	1.90×10^6	0.383		
			0.6	1029 000	7.06×10^7	0.015		

In the case of a crack length of 0.1 m, $\frac{\Delta K}{E} = \frac{(1.25 \times 10^{3})}{10 \times 10^{6}} \mathrm{m}^{\frac{1}{2}} = 1.25 \times 10^{-4} \mathrm{m}^{\frac{1}{2}}$. In his work on non-propagating fatigue cracks Harrison[C4] found that the threshold value of $\frac{(\Delta K)}{E}$, that is the value of $\frac{\Delta K}{E}$ below which cracks would not propagate, was between $1.5 \times 10^{-4} \mathrm{m}^{\frac{1}{2}}$ and $1.5 \times 10^{-5} \mathrm{m}^{\frac{1}{2}}$. Therefore the 10% stress level would have produced no crack propagation until the crack length was at least 0.1 m. It is also likely that the changes of stress occurring in a programme produce residual stress at the crack tip, which might cause the crack to remain stationary for a few cycles, or to reduce the rate of crack growth.

A further observation made using the scanning electron microscope is shown in Fig. C9. This was the presence of smaller striations within a striation caused by the application of one load cycle in a constant amplitude specimen. It is thought that these sub-striations are the same as those reported by Tomkins[C5], being caused by incremental slipping at the crack tip during the application of a single load cycle. The number and spacing of these sub-striations would depend on the ductility of the material. Also the spacing of the striations, and therefore the distance propagated by the crack during one cycle, would depend on the spacing and number of sub-striations, so that the rate of crack growth is directly related to the material ductility. These observations may prove to be useful in future work on fatigue crack propagation.

CONCLUSIONS

From the crack propagation studies it was found that the fracture mechanics approach was applicable in examining the results. It was found that all the results approximately obeyed the law $\frac{da}{dN} = C\,(\Delta K)^4$, where C is a constant. The value of C in the constant amplitude test results differed from that for the programmed test results. It was also found that for each of the two sets of results the value of C depended on the maximum applied stress range. It was this latter variation in C which largely dictated the width of the scatter bands in the graphs of $\frac{da}{dN}$ v ΔK.

An examination of the fracture surfaces revealed that fractography was a useful method of analysing crack propagation. The examination showed that the dark markings that appear at intervals for the programme loaded specimens coincided with times of low stress in the programme, with slow crack propagation. On a microscopic level it was found that striations occur at each cycle of loading for constant amplitude loaded specimens, and presumably for each damaging cycle in the case of programme loaded specimens. The scanning electron microscope examination also revealed the presence of substriations, thought to be caused by incremental slipping in the material at the tip of a propagating crack.

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TABLE 1. Chemical analyses.

Material	Analysed by	Extrusion size	Fe	Cu	Si	Mn	Mg	Ti	Cr	Zn	Ni
D74SGB	Alcan Industries	5 in. x $^3/_8$ in. Batch 1	0.20	0.02	0.05	0.26	1.30	-	0.13	4.32	-
	Alcan Industries	5 in. x $^3/_8$ in. Batch 2	0.25	0.04	0.07	0.28	1.29	0.01	0.11	4.44	-
	Alcan Industries	$1\frac{1}{2}$ in x $^5/_{16}$ in. All batches	0.17	0.01	0.07	0.27	1.30	0.01	0.14	4.50	-
	The Welding Institute	5in. x $^3/_8$ in. Batch 1	0.16	Trace	0.045	0.25	1.38	0.01	0.13	4.57	-
H48	High duty alloys	5 in. x $^3/_8$ in.	0.23	0.02	0.17	0.23	2.59	<0.01	0.16	4.59	<0.01

TABLE 2. Mechanical properties.

Material	Tested by	Extrusion size	0.1% proof tonf/in^2	0.2% proof tonf/in^2	UTS tonf/in^2	Elongation % 4 in. g.l.
D74SGB	Alcan Industries	5 in. x $^3/_8$ in. Batch 1	19.3	-	22.7	22
	Alcan Industries	5 in. x $^3/_8$ in. Batch 2	21.3	-	24.8	18
	Alcan Industries	$1\frac{1}{2}$ in. x $^5/_{16}$ in. All batches	21.0-21.9	-	24.2-25.8	19-20
	The Welding Institute	5 in. x $^3/_8$ in. Batch 1	19.8	20.3	23.3	16
H48	High duty alloys	5 in. x $^3/_8$ in.	27.3	-	31.8	14

TABLE 3. Heat treatment.

Extruding temperature	460–480°C
Quench temperature	440–460°C
Age for one hour at 100°C followed by twelve hours at 135°C	

TABLE 4. Programmed test results for notched specimens of D74S (programme 1).

Specimen no.	Failure at: Stage no.	Failure at: Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma \frac{n}{N}$	Total cycles x 10^6
a) S min = -2.0 tonf/in^2								
PNA/1	34	90%	12.7	29	470	0.062		
			11.4	4 164	1 020	4.082		
			10.2	11 410	2 280	5.004		
			8.9	29 020	6 080	4.772	14.84	0.384
			6.3	64 500	73 100	0.883		
			3.8	114 600	2.78×10^6	0.041		
			1.3	160 100	6.24×10^9	-		
PNA/2	26	70%	9.5	44	3 810	0.012		
			8.5	6 253	8 470	0.738		
			7.6	17 080	18 900	0.903		
			6.6	43 240	52 300	0.827	2.65	0.576
			4.7	96 700	601 000	0.161		
			2.8	171 200	2.5×10^7	0.007		
			1.0	241 700	4.1×10^{11}	-		
PNA/3	24	90%	6.7	173	46 900	0.004		
			6.0	24 470	104 000	0.235		
			5.3	67 040	253 000	0.265		
			4.7	171 500	601 000	0.285	0.84	2.296
			3.3	385 000	7.66×10^6	0.050		
			2.0	683 300	2.81×10^8	0.002		
			0.7	964 500	5.36×10^{11}	-		
b) S min = 0								
PN/1	34	90%	13.5	14	650	0.021		
			12.2	2 014	1 100	1.831		
			10.8	5 580	2 090	2.670		
			9.4	14 110	4 300	3.280	9.19	0.184
			6.7	31 020	25 100	1.236		
			4.0	55 020	368 000	0.150		
			1.3	76 050	1.28×10^8	-		
PN/2	24	90%	10.8	29	2 080	0.014		
			9.7	4 032	3 650	1 105		
			8.6	11 080	6 830	1.622		
			7.6	28 330	13 000	2.179	5.84	0 376
			5.4	63.210	77 100	0.820		
			3.2	111 600	1.18×10^6	0.095		
			1.1	157 700	3.06×10^8	0.001		
PN/3	22	90%	9.5	40	4 070	0.010		
			8.5	5 630	7 260	0.775		
			7.6	15 740	13 000	1.211		
			6.6	40 260	27 100	1.485	4.11	0.536
			4.7	90 020	159 000	0.566		
			2.8	159 300	2.36×10^6	0.067		
			1.0	224 900	5.03×10^8	-		
PN/4	34	90%	7.5	62	13 900	0.004		
			6.8	8 800	23 200	0.379		

TABLE 4. (Continued)

Specimen no.	Failure at: Stage no	Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma\frac{n}{N}$	Total cycles x 10^6
b) S min = 0 (Continued)								
			6.0	24 240	44 500	0.545		
			5.3	61 820	85 000	0.727		
			3.8	138 300	481 000	0.287	1.96	0.824
			2.3	245 600	6.57 x 10^6	0.037		
			0.75	345 000	2.25 x 10^9	-		
PN/5	44	70%	6.0	165	44 500	0.004		
			5.4	23 320	77 100	0.302		
			4.8	64 130	142 000	0.452		
			4.2	163 600	286 000	0.572	1.58	2.191
			3.0	367 200	1.65 x 10^6	0.223		
			1.8	652 000	2.35 x 10^7	0.028		
			0.6	920 400	7.19 x 10^9	-		
c) S min = +2.5								
PNT/1	22	90%	11.8	13	2 160	0.006		
			10.6	1 844	3 140	0.587		
			9.4	5 250	4 770	1.100		
			8.3	13 420	7 360	1.823	5.11	0.176
			5.9	29 690	24 100	1.232		
			3.5	52 100	149 000	0.350		
			1.2	73 650	6.21 x 10^6	0.012		
PNT/2	44	70%	9.0	18	5 550	0.003		
			8.1	2 544	8 000	0.318		
			7.2	7 000	12 100	0.578		
			6.3	17 740	19 200	0.924	2.64	0.231
			4.5	38,740	62 100	0.624		
			2.7	68,460	368 000	0.186		
			0.9	96 850	1.69 x 10^7	0.006		
PNT/3	12	90%	5.8	76	25 600	0.003		
			5.2	10 610	37 500	0.283		
			4.6	29 400	57 500	0.511		
			4.1	75 360	85 900	0.877	2.43	1.008
			2.9	169 100	287 000	0.589		
			1.7	299 300	1.85 x 10^6	0.162		
			0.6	424 200	6.95 x 10^7	0.006		

TABLE 5. Programmed test results for welded specimens of D74S (programme 2).

Specimen no.	Failure at: Stage no.	Failure at: Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma \frac{n}{N}$	Total cycles $\times 10^6$
a) - S min = -1.25 tonf/in^2								
PWA/1	13	90%	13.0	25	5 060	0.006		
			11.7	3 913	7 470	0.524		
			10.4	10 740	11 500	0.934		
			9.1	27 650	18 600	1.457	4.19	0.366
			6.5	61 850	63 700	0.971		
			3.9	108 700	411 000	0.265		
			1.3	155 300	2.27×10^7	0.007		
PWA/2	3	80%	11.5	57	7 940	0.007		
			10.3	8 050	11 900	0.677		
			9.2	22 280	17 900	1.242		
			8.0	57 060	29 800	1.917	5.31	0.761
			5.7	127 900	103 000	1.243		
			3.4	226 390	1.07×10^5	0.213		
			1.2	319 400	3.03×10^7	0.011		
PWA/3	25	80%	10.0	65	13 200	0.005		
			9.0	9 221	19 400	0.475		
			8.0	25 200	29 800	0.846		
			7.0	64 110	48 600	1.319	3.75	0.855
			5.0	143 700	166 000	0.865		
			3.0	254 600	1.07×10^6	0.238		
			1.0	359 400	5.90×10^7	0.006		
b) - S min = 0								
PW/1	34	90%	14.0	11	3 360	0.003		
			12.6	1 590	6 250	0.244		
			11.0	4 410	7 390	0.597		
			9.8	11 120	11 800	0.943	2.60	0.144
			7.0	24 320	38 900	0.625		
			4.2	43 110	236 000	0.183		
			1.4	59 240	1.15×10^7	0.006		
PW/15	24	90%	13.3	26	4 020	0.006		
			12.0	3 696	5 790	0.630		
			10.7	9 911	8 680	1.142		
			9.3	25 355	14 200	1.786	5.17	0.336
			6.7	56 497	45 400	1.244		
			4.0	99 735	281 000	0.355		
			1.3	140 882	1.49×10^7	0.009		
PW/2	22	90%	13.0	16	4 360	0.004		
			11.7	2 288	6 330	0.361	3.03	0.216
			10.4	6 110	9 600	0.668		
			9.1	16 400	15 400	1.065		
			6.5	36 390	50 500	0.721		
			3.9	64 000	307 000	0.208		
			1.3	90 460	1.49×10^7	0.006		

TABLE 5. (Continued).

Specimen no.	Failure at: Stage no.	Failure at: Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma \frac{n}{N}$	Total cycles x 10^6
b) - S min = 0 (Continued).								
PW/3	22	90%	12.0	31	5 790	0.005		
			10.8	4 348	8 400	0.518		
			9.6	12 240	12 700	0.964		
			8.9	31 310	20 400	1.535	4.38	0.416
			6.0	69 310	67 000	1.043		
			3.6	123 660	408 000	0.303		
			1.2	174 500	1.98×10^7	0.008		
PW/16	25	80%	11.9	35	5 960	0.006		
			10.7	5 005	8 680	0.577		
			9.5	13 438	13 200	1.018		
			8.3	34 304	21 300	1.611		
			6.0	76 606	67 000	1.143	4.70	0.456
			3.6	135 465	408 000	0.332		
			1.2	191 306	1.98×10^7	0.010		
PW/4	12	90%	10.5	46	9 280	0.005		
			9.5	6 362	13 200	0.482		
			8.3	17 740	21 300	0.833		
			7.4	45 540	32 000	1.423	3.93	0.611
			5.3	102 000	104 000	1.072		
			2.9	198 000	875 000	0.226		
			0.7	277 700	1.33×10^8	0.002		
PW/5	34	90%	10.5	50	9 280	0.005		
			9.5	7 172	13 200	0.543		
			8.3	19 570	21 300	0.919		
			7.4	49 890	32 000	1.559	4.33	0.664
			5.3	111 500	104 000	1.072		
			2.9	198 000	875 000	0.226		
			0.7	277 700	1.33×10^8	0.002		
PW/17	24	90%	9.8	74	11 800	0.006		
			8.8	10 512	17 300	0.608		
			7.8	28 567	26 500	1.078		
			6.9	73 083	90 900	1.786	5.02	0.976
			4.9	163 745	137 000	1.195		
			2.9	409 810	3.77×10^7	0.011		
PW/6	24	90%	9.5	77	13 200	0.006		
			8.3	10 816	21 300	0.508		
			7.4	29 730	32 000	0.929		
			6.8	76 040	43 100	1.764	4.63	1.016
			4.7	170 500	159 000	1.072		
			2.9	302 200	875 000	0.345		
			0.7	426 600	1.33×10^8	0.003		
PW/7	34	90%	9.5	53	13 200	0.004		
			8.3	7 616	21 300	0.357		
			7.4	20 740	32 000	0.648		
			6.8	52 870	43 100	1.227	3.22	0.704

TABLE 5. (Continued).

Specimen no.	Failure at: Stage no.	Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma\frac{n}{N}$	Total cycles x 10^6
b) - S min = 0 (continued)								
			4.7	118 200	159 000	0.743		
			2.9	209 900	875 000	0.240		
			0.7	294 500	1.33 x 10^8	0.002		
PW/8	20	70%	9.5	70	13 200	0.005		
			8.5	9 858	19 200	0.513		
			7.6	27 230	29 100	0.936		
			6.6	69 800	46 600	1.498	4.29	0.935
			4.7	157 100	153 000	1.027		
			2.8	278 400	931 000	0.299		
			0.9	393 000	4.52 x 10^7	0.009		
PW/9	23	100%	8.0	86	18 100	0.005		
			7.2	12 084	35 200	0.343		
			6.4	33.230	53 300	0.623		
			5.6	84 990	85 600	0.993	2.85	1.135
			4.0	190 600	281 000	0.678		
			2.4	337 900	1.71 x 10^6	0.198		
			0.8	477 000	8.29 x 10^7	0.006		
PW/10	22	90%	7.0	154	38 900	0.004		
			6.3	21 732	56 400	0.385		
			5.6	60 050	85 500	0.702		
			4.9	153 600	137 000	1.121	3.21	2.056
			3.5	344 800	450 000	0.766		
			2.1	611 900	2.74 x 10^6	0.223		
			0.7	863 600	1.33 x 10^8	0.006		
PW/18	13	80%	6.9	289	40 900	0.007		
			6.2	41 003	59 800	0.686		
			5.5	112 346	91 100	1.233		
			4.8	287 204	147 000	1.959	6.60	3.848
			3.4	645 029	499 000	1.293		
			2.1	1144 885	2740 000	0.418		
			0.7	1617 568	1.33 x 10^8	0.012		
PW/11	3	80%	6.2	519	5 970	0.009		
			5.6	73 352	8 550	0.858		
			4.9	201 947	13 700	1.474	6.94	6.92
			4.3	516 286	21 700	2.379		
			3.1	1160 313	69 700	1.679		
			1.9	2060 420	3.90 x 10^6	0.528		
			0.6	2907 784	2.29 x 10^8	0.013		
PW/12	13	80%	5.5	586	91 400	0.006		
			5.0	82 786	128 000	0.647		
			4.3	227 740	218 000	1.045		
			3.9	582 305	307 000	1.897	5.25	7.81
			2.8	1303 821	990 000	1.322		
			1.6	2323 975	7.22 x 10^6	0.322		
			0.6	3281 560	2.29 x 10^8	0.014		

TABLE 5. (Continued).

Specimen no.	Failure at: Stage no.	Failure at: Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma \frac{n}{N}$	Total cycles x 10^6
c) - S min = +1.75								
PWT/1	12	90%	14.0	19	2 230	0.009		
			12.6	2 546	3 160	0.806		
			11.2	7 250	4 660	1.555		
			9.8	18 710	7 230	2.587	7.51	0.248
			7.0	41 760	21 900	1.907		
			4.2	72 980	117 000	0.624		
			1.4	104 800	4.35×10^6	0.024		
PWT/2	34	90%	12.0	17	3 710	0.004		
			10.8	2 534	5 250	0.483		
			9.6	6 750	7 730	0.873		
			8.4	17 090	12 000	1.424	4.18	0.224
			6.0	37 720	36 300	1.039		
			3.6	66 930	195 000	0.343		
			1.2	92 850	7.23×10^6	0.013		
PWT/3	22	90%	10.25	34	6 230	0.005		
			9.2	4 820	8 890	0.542		
			8.2	13 410	13 000	1.031		
			7.2	24 290	19 900	1.723	4.98	0.456
			5.1	76 620	61 900	1.238		
			3.1	135 500	318 000	0.426		
			1.0	191 300	1.32×10^7	0.014		
PWT/4	24	90%	8.0	83	14 100	0.006		
			7.2	11 661	19 900	0.586		
			6.4	32 060	29 300	1.094		
			5.6	82 000	45 500	1.802	5.28	1.114
			4.0	183 900	138 000	1.332		
			2.4	326 000	739 000	0.441		
			0.8	460 200	2.74×10^7	0.014		
PWT/5	12	90%	6.0	184	36 300	0.005		
			5.4	25 951	51 300	0.506		
			4.8	71 380	75 600	0.944		
			4.2	182 700	117 000	1.562	4.57	2.448
			3.0	410 500	355 000	1.156		
			1.8	728 000	1.90×10^6	0.383		
			0.6	1029 000	7.06×10^7	0.015		

TABLE 6. Programmed test results for welded specimens of D74S (programme 1 with 10% load levels omitted).

Specimen no.	Failure at: Stage no.	Failure at: Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma \frac{n}{N}$	Total cycles x 10^6
PW/13	45	90%	6.0	369	67 000	0.006		
			5.4	52 152	97 300	0.536		
			4.8	143 419	147 000	0.976	4.42	2.85
			4.2	366 786	236 000	1.554		
			3.0	822 393	776 000	1.060		
			1.8	1461 930	4720 000	0.310		
PW/14	24	90%	5.4	506	97 000	0.005		
			4.9	71 537	137 000	0.522		
			4.3	196 471	218 000	0.901	3.94	3.90
			3.8	502 467	337 000	1.491		
			2.7	1127 802	1130 000	0.998		
			1.6	2005 335	7220 000	0.028		

TABLE 7. Programmed test results for welded specimens of D74S (programme 2 - slow rise/rapid fall).

Specimen no.	Failure at: Stage no.	Failure at: Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma\frac{n}{N}$	Total cycles x 10^6
PW2/1	34	90%	14.5	17	2 970	0.006		
			13.0	2 518	4 360	0.577		
			11.6	6 745	6 520	1.035		
			10.2	17 017	10 300	1.652	4.64	0.221
			7.2	37 151	35 200	1.055		
			4.3	65 460	217 000	0.302		
			1.5	92 844	8.98×10^6	0.101		
PW2/2			12.0	46	5 790	0.008		
			10.6	6 501	8 400	0.774		
			9.6	17 962	12 700	1.414	6.43	0.611
			8.4	45 954	20 400	2.253		
			6.0	102 377	67 000	1.528		
			3.6	181 650	408 000	0.445		
			1.2	256 124	1.98×10^7	0.013		
PW2/3			9.7	93	12 300	0.008		
			8.7	13 144	18 000	0.730		
			7.8	36 336	26 500	1.373	6.24	1.249
			6.8	93 242	43 100	2.163		
			4.9	209 239	137 000	1.528		
			2.9	372 210	875 000	0.425		
			1.0	525 052	3.77×10^7	0.014		
PW2/4			8.0	148	24 200	0.006		
			7.2	20 917	35 200	0.594		
			6.4	57 606	53 300	1.081	4.93	1.971
			5.6	147 378	85 500	1.724		
			4.0	330 368	281 000	1.176		
			2.4	586 590	1.71×10^6	0.343		
			0.8	827 596	8.29×10^7	0.010		
PW2/5			6.6	314	47 900	0.007		
			5.9	44 378	71 100	0.624		
			5.3	122 111	104 000	1.174	5.37	4.181
			4.6	312 235	164 000	1.904		
			3.3	700 748	554 000	1.269		
			2.0	1.245×10^6	3.25×10^6	0.388		
			0.7	1.757×10^6	1.33×10^8	0.013		
PW2/6	12	90%	6.6	402	47 900	0.008		
			5.9	56 863	71 100	0.800		
			5.3	156 716	104 000	1.507		
			4.6	400 773	164 000	2.444	6.89	5.370
			3.3	900 034	554 000	1.625		
			2.0	1598 940	3250 000	0.492		
			0.7	2256 273	1.33×10^8			

TABLE 8. Results of tests with programme 3 (rapid rise/slow fall) on welded specimens of D74S.

Specimen no.	Failure at: Stage no.	Failure at: Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma \frac{n}{N}$	Total cycles x 10^6
PW3/1	24	90%	11.2	50	7 390	0.007		
			10.1	7 005	10 500	0.661		
			9.0	19 129	16 000	1.196		
			7.9	49 046	25 400	1.931	5.48	0.656
			5.6	110 267	85 600	1.288		
			3.4	195 015	499 000	0.391		
			1.1	275 332	2.69 x 10^7	0.010		
PW3/2	35	90%	10.0	96	11 000	0.009		
			9.0	13 513	16 000	0.845		
			8.0	36 840	24 200	1.523		
			7.0	94 238	38 900	2.423	6.95	1.261
			5.0	211 714	128 000	1.654		
			3.0	375 120	776 000	0.483		
			1.0	529 852	3.77 x 10^7	0.014		
PW3/3	44	80%	9.6	108	12 700	0.009		
			8.6	15 264	18 800	0.812		
			7.7	41 847	27 800	1.505		
			6.7	106 627	45 400	2.349	6.82	1.430
			4.8	239 427	146 000	1.640		
			2.9	425 760	875 000	0.487		
			1.0	601 084	3.77 x 10^7	0.016		
PW3/4	4	70%	8.7	153	18 000	0.009		
			7.8	21 624	26 500	0.816		
			7.0	59 716	38 900	1.535		
			6.1	152 213	63 200	2.408	6.96	2.040
			4.4	341 972	200 000	1.710		
			2.6	607 410	1290 000	0.471		
			0.9	857 208	5.47 x 10^7	0.016		
PW3/5	36	80%	7.6	243	29 100	0.008		
			6.8	34 344	43 100	0.797		
			6.1	93 999	63 200	1.487		
			5.3	240 356	104 000	2.311	6.70	3.221
			3.8	540 161	337 000	1.603		
			2.3	959 710	1990 000	0.482		
			0.8	1353 444	8.29 x 10^7	0.016		

TABLE 9. Results of tests with programme 4 (vertical rise/slow fall) on welded specimens of U74S.

Specimen no.	Failure at:		Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma\frac{n}{N}$	Total cycles $\times 10^6$
	Stage no.	Load level						
PW4/1	2	90%	10.0	104	11 000	0.009		
			9.0	14 164	16 000	0.885		
			8.0	33 473	24 200	1.590		
			7.0	58 406	35 900	2.530	6.26	1.320
			5.0	221 197	128 000	1.725		
			3.0	393 030	736 000	0.506		
			1.0	554 720	3.77×10^7	0.015		
PW4/2	2	90%	6.9	255	40 900	0.006		
			6.2	35 736	59 800	0.598		
			5.5	97 944	91 400	1.072	4.55	3 360
			4.8	250 456	147 000	1.704		
			3.4	563 052	499 000	1.128		
			2.1	1000 440	2740 000	0.365		
			0.7	1412 019	1.33×10^8	0.011		

TABLE 10. Results of tests with programme 5 (slow rise/vertical fall) on welded specimens of D74S.

Specimen no.	Failure at: Stage no	Failure at: Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma\frac{n}{N}$	Total cycles x 10^6
PW5/1	6	90%	14.0	12	3 509	0.003		
			12.6	1 924	4 832	0.399		
			11.2	5 327	7 323	0.727		
			9.8	14 910	11 720	1.271	3.60	0.300
			7.0	33 512	38 500	0.871		
			4.2	59 550	234 400	0.254		
			1.4	84 056	1.139 x 10^7	0.007		
PW5/2	6	90%	11.9	30	6 034	0.005		
			10.7	4 296	9 372	0.459		
			9.5	12 820	13 320	0.963		
			8.3	32 820	21 300	1.541	4.37	0.440
			5.9	73 727	69 900	1.052		
			3.6	131 010	424 300	0.309		
			1.2	184 919	1.061 x 10^7	0.009		
PW5/3	6	90%	10.8	33	8 403	0.004		
			9.7	4 990	12 230	0.408		
			8.6	13 963	18 560	0.753		
			7.6	35 784	29 630	1.208	3.45	0.450
			5.4	80 427	97 270	0.826		
			3.2	142 920	591 700	0.242		
			1.1	201 729	2.871 x 10^7	0.007		
PW5/4	6		9.8	90	11 630	0.008		
			8.9	13 040	16 920	0.771		
			7.9	36 125	25 700	1.406		
			6.9	92 442	41 330	2.240	6.42	1.240
			4.9	207 772	135 100	1.536		
			2.9	369 210	823 900	0.447		
			1.0	521 134	3.975 x 10^7	0.013		
PW5/5	5	80%	7.9	270	25 140	0.011		
			7.1	38 204	36 430	1.049		
			6.3	104 976	55 170	1.967		
			5.5	271 362	88 290	3.075	8.17	3.640
			4.0	609 907	291 100	2.093		
			2.4	1083 810	1.759 x 10^6	0.616		
			0.8	1529 779	8.588 x 10^7	0.018		
PW5/6			7.6	539	28 180	[illegible]02		
			6.85	76 054	40 270	[illegible]9		
			6.1	208 873	60 530	3.45		
			5.3	535 675	100 500	5.33	15.5	7.176
			3.8	1202 267	327 300	3.66		
			2.3	2137 710	1923 000	1.11		
			0.8	3018 172	8.0 x 10^7	0.04		

TABLE 11. Results of tests using programme 1 (basic programme) on welded specimens of H4S material.

Specimen no.	Failure at: Stage no.	Failure at: Load level	Stress range ton/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma \frac{n}{N}$	Total cycles x 10^6
2/PW/1	21	70%	8.2	106	22 230	0.005		
			7.4	14 946	32 250	0.320		
			6.6	41 220	48 910	0.632		
			5.7	105 577	75 390	1.121	3.51	1.415
			4.1	237 513	257 400	0.955		
			2.5	421 305	1.566 x 10^6	0.420		
			0.8	594 696	7.594 x 10^7	0.028		
2/PW/2	13	90%	8.2	106	22 230	0.005		
			7.4	14 843	32 250	0.320		
			6.6	41 060	48 910	0.630		
			5.7	105 185	75 390	1.120	3.50	1.408
			4.1	236 181	257 400	0.960		
			2.5	418 375	1.566 x 10^6	0.419		
			0.8	592 280	7.596 x 10^7	0.025		
2/PW/3	12	100%	8.0	142	24 250	0.004		
			7.2	19 928	35 210	0.396		
			6.4	55 052	53 350	0.726		
			5.6	140 969	85 530	1.400	4.30	1.588
			4.0	316 629	250 800	1.231		
			2.4	561 295	1.708 x 10^6	0.525		
			0.8	793 976	8.287 x 10^6	0.035		

TABLE 12. Programmed test results for welded specimen of H48 (programme 1. R = +0.5).

Specimen no.	Failure at: Stage no.	Failure at: Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma\frac{n}{N}$	Total cycles x 10^6
2/PWT/1	25	90%	11.62	8	6 530	0.001	1.04	0.096
			10.94	1 043	8 120	0.128		
			9.66	2 885	12 700	0.227		
			8.44	7 405	20 700	0.357		
			6.16	16 226	64 600	0.251		
			3.82	28 227	362 000	0.077		
			1.38	39 996	14.3 x 10^6	0.003		
2/PWT/2	24	100%	11.59	5	6 600	0.001	0.53	0.056
			10.45	624	9 590	0.065		
			9.31	1 731	14 600	0.119		
			8.17	4 443	23 300	0.191		
			5.82	9 545	79 400	0.120		
			3.56	16 337	468 000	0.035		
			1.26	23 204	19.9 x 10^6	0.001		
2/PWT/3	23	90%	9.80	28	12 100	0.002	2.53	0.376
			9.37	3 929	14 200	0.276		
			8.40	10 963	21 100	0.520		
			7.41	26 658	33 300	0.844		
			5.60	60 129	91 200	0.690		
			3.73	107 010	596 000	0.187		
			1.46	151 128	11.7 x 10^6	0.013		
2/PWT/4	13	90%	9.01	49	16 400	0.002	2.64	0.648
			8.16	6 662	23 400	0.284		
			7.27	18 712	35 500	0.526		
			6.32	48 201	58 900	0.818		
			4.90	108 432	148 000	0.734		
			3.15	191 761	728 000	0.263		
			1.28	272 668	18.8 x 10^6	0.014		
2/PWT/5	3	80%	7.96	66	25 600	0.002	2.56	0.881
			7.32	9 152	34 700	0.264		
			6.58	25 396	50 900	0.498		
			5.74	65 562	83 400	0.786		
			4.19	147 502	260 000	0.567		
			2.57	261 580	1.52 x 10^6	0.172		
			0.93	369 424	59.7 x 10^6	0.006		
2/PWT/6	23	90%	7.38	73	33 600	0.002	2.13	0.976
			6.75	10 119	46 400	0.218		
			6.09	28 273	67 400	0.419		
			5.32	72 567	110 000	0.661		
			4.12	163 208	276 000	0.591		
			2.68	289 807	1.31 x 10^6	0.222		
			1.26	403 008	19.4 x 10^6	0.021		
2/PWT/7	13	90%	6.66	85	48 700	0.002		
			6.10	11 714	64 600	0.181		

TABLE 12. (Continued)

Specimen no.	Failure at: Stage no.	Failure at: Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma\frac{n}{N}$	Total cycles x 10^6
2/PWT/7			5.43	22 560	102 000	0.221	1.63	1.128
(continued)			4.88	83 745	150 000	0.558		
			3.71	188 604	403 000	0.468		
			2.47	334 441	1.75 x 10^6	0.191		
			0.99	474 172	47.6 x 10^6	0.010		
2/PWT/8	27	70%	5.12	170	126 000	0.001		
			4.72	23 607	169 000	0.139		
			4.18	65 372	262 000	0.249		
			3.77	167 608	377 000	0.444	1.35	2.257
			2.86	377 000	1.03 x 10^6	0.365		
			1.88	670 287	4.70 x 10^6	0.143		
			0.91	946 764	64.6 x 10^6	0.014		
2/PWT/9	13	90%	4.53	352	196 000	0.002		
			4.13	48 708	274 000	0.178		
			3.72	135 266	400 000	0.338	1.81	4.688
			3.32	347 363	603 000	0.576		
			2.53	783 213	1.61 x 10^6	0.487		
			1.71	1.39 x 10^6	6.62 x 10^6	0.211		
			0.81	1.97 x 10^6	98.3 x 10^6	0.020		
2/PWT/10	13	90%	3.82	435	263 000	0.001		
			3.49	60 320	503 000	0.120		
			3.12	167 330	746 000	0.224	1.26	5.794
			2.83	429 490	1.07 x 10^6	0.400		
			2.18	968 745	2.75 x 10^7	0.352		
			1.46	1.72 x 10^6	11.7 x 10^6	0.147		
			0.75	2.43 x 10^6	130 x 10^6	0.019		

TABLE 13. Programmed test results for welded specimens of HHS (programme 1. R = -1).

Specimen no.	Failure at: Stage no.	Failure at: Load level	Stress range $tonf/in^2$	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma\frac{n}{N}$	Total cycles $\times 10^6$
2/FWA/1	24	100%	15.2	26	14 500	0.002		
			13.9	3 536	18 600	0.190		
			12.4	9 809	25 709	0.382		
			10.9	25 177	36 800	0.684	2.11	0.336
			7.74	56 312	96 500	0.587		
			4.81	99 567	408 000	0.244		
			1.62	140 748	7.59×10^6	0.015		
2/PWA/2	52	50%	14.2	36	17 600	0.002		
			12.8	4 992	23 500	0.213		
			11.3	13 848	33 300	0.416		
			10.0	35 544	46 800	0.759	2.41	0.480
			7.14	80 093	120 000	0.667		
			4.48	142 680	442 000	0.323		
			1.77	201 504	5.93×10^6	0.034		
2/PWA/3	25	90%	14.3	36	17 800	0.002		
			12.78	5 326	18 600	0.285		
			11.28	14 425	33 500	0.431	2.55	0.496
			9.98	37 025	47 100	0.786		
			7.10	83 036	122 000	0.581		
			4.46	147 127	448 000	0.328		
			1.76	207 916	6.02×10^6	0.034		
2/PWA/4	45	80%	14.08	30	18 000	0.002		
			12.71	4 160	23 900	0.174		
			11.22	11 454	33 900	0.337		
			9.95	29 222	47 500	0.615	1.94	0.391
			7.07	65 337	123 000	0.529		
			4.45	115 904	450 000	0.251		
			1.75	163 930	6.12×10^6	0.027		
2/PWA/5	3	80%	11.72	45	30 000	0.001		
			10.44	6 240	41 500	0.150		
			9.20	17 536	59 000	0.296		
			8.14	44 828	83 200	0.538	1.71	0.601
			5.86	100 735	208 000	0.483		
			3.60	178 350	814 000	0.219		
			1.36	251 880	1.24×10^6	0.020		
2PWA/6	24	100%	9.76	93	50 100	0.002		
			8.78	12 896	67 300	0.191		
			7.81	35 774	93 400	0.383		
			6.83	91 822	136 000	0.676	2.25	1.252
			5.00	207 000	325 000	0.637		
			3.18	368 590	1.15×10^6	0.320		
			1.30	520 552	14.0×10^6	0.037		
2/PWA/7	2	70%	9.71	99	50 800	0.002		
			8.73	13 728	68 400	0.201		
			7.77	38 082	94 800	0.402		
			6.79	97 899	138 000	0.709	2.35	1.321
			4.91	220 993	332 000	0.665		
			2.16	392 370	14.3×10^6	0.039		

TABLE 13. (Continued).

Specimen no.	Failure at: Stage no.	Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma\frac{n}{N}$	Total cycles x 10^6
2/PWA/8	2	70%	6.93	138	130 000	0.001		
			6.30	19 136	170 000	0.112		
			5.62	53 084	234 000	0.226		
			4.99	136 530	327 000	0.418	1.45	1.841
			3.74	307 848	732 000	0.421		
			2.44	546 940	2.41 x 10^6	0.226		
			1.21	772 432	17.2 x 10^6	0.045		
2/PWA/9	20	30%	5.62	235	234 000	0.001		
			5.22	32 550	288 000	0.113		
			4.70	90 418	386 000	0.233		
			4.15	232 193	547 000	0.424	1.51	3.135
			3.16	523 964	1.17 x 10^6	0.447		
			2.12	931 867	3.58 x 10^6	0.260		
			0.88	1.316 x 10^6	41.8 x 10^6	0.031		
2/PWA/10	16	50%	4.78	469	369 000	0.001		
			4.29	64 998	499 000	0.130		
			3.82	180 430	690 000	0.261		
			3.43	463 229	932 000	0.497	1.79	6.249
			2.64	1.044 x 10^6	1.94 x 10^6	0.538		
			1.77	1.856 x 10^6	5.93 x 10^6	0.313		
			0.81	2.624 x 10^6	52.7 x 10^6	0.050		

TABLE 14. Programmed test results for welded specimens of H48 using randomised programme (programme 11. R = 0).

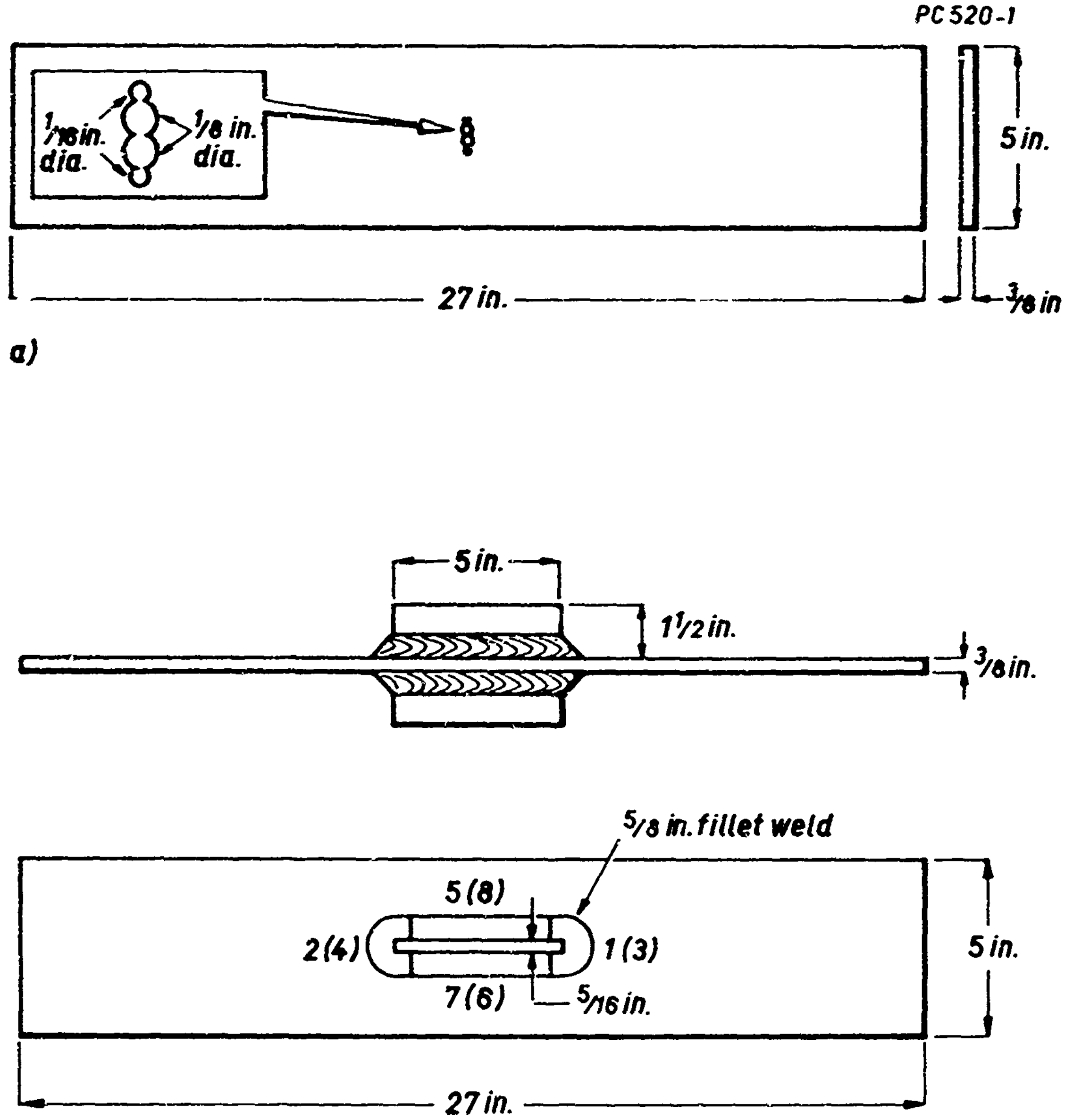
Specimen no.	Failure at: Stage no.	Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma\frac{n}{N}$	Total cycles x 10^6
2/PW11/1	41	70%	17.22	9	4 410	0.002		
			15.73	1 142	5 680	0.202		
			14.12	3 388	7 670	0.442		
			12.45	8 140	10 900	0.749	2.37	0.112
			8.99	16 526	27 000	0.614		
			5.55	34 146	103 000	0.330		
			2.11	48 369	1.53 x 10^6	0.032		
2/PW11/2	41	70%	15.16	18	6 290	0.003		
			13.84	2 390	8 110	0.295		
			12.26	6 595	11 400	0.580		
			10.83	17 064	16 100	1.062	3.45	0.232
			7.89	36 566	38 800	0.944		
			5.06	69 816	134 000	0.521		
			1.84	98 736	2.24 x 10^6	0.044		

TABLE 14. (Continued).

Specimen no.	Failure at: Stage no.	Load level	Stress range tonf/in^2	No. of cycles at stress n	Cycles to cause failure at stress N	$\frac{n}{N}$	$\Sigma \frac{n}{N}$	Total cycles x 10^6
2/PW11/3	38	70%	12.92	30	9 820	0.003		
			11.84	4 054	12 500	0.324		
			10.58	11 211	17 100	0.654		
			9.22	28 756	25 100	1.143	3.77	0.338
			6.72	62 558	60 600	1.032		
			4.31	117 376	209 000	0.562		
			1.62	163 476	3.19 x 10^6	0.051		
2/PW11/4	35	70%	12.01	45	12 000	0.004		
			10.89	6 134	15 800	0.387		
			9.52	16 981	23 000	0.738		
			8.41	43 055	32 500	1.328	4.52	0.587
			6.31	95 958	72 300	1.328		
			4.00	175 378	257 000	0.682		
			1.44	247 421	4.43 x 10^6	0.056		
2/PW11/5	27	90%	9.50	59	23 100	0.003		
			8.70	8 149	29 600	0.276		
			7.72	22 751	41 200	0.552		
			6.82	37 058	58 200	0.959	3.43	0.781
			5.17	129 358	126 000	1.026		
			3.37	231 822	415 000	0.558		
			1.30	329 376	5.90 x 10^6	0.056		
2/PW11/6	27	90%	7.47	110	45 200	0.002		
			6.77	15 241	59 400	0.257		
			6.05	42 369	81 300	0.528		
			5.37	107 429	113 000	0.949	3.42	1.461
			4.16	242 918	231 000	1.051		
			2.70	433 952	769 000	0.576		
			1.11	614 425	9.16 x 10^6	0.067		
2/PW11/7	32	70%	5.64	266	98 900	0.003		
			5.10	36 918	131 000	0.280		
			4.53	102 377	182 000	0.558		
			4.05	262 222	249 000	1.052	3.75	3.544
			3.08	590 278	533 000	1.102		
			2.08	1.055 x 10^6	1.59 x 10^6	0.656		
			0.93	1.489 x 10^6	15.0 x 10^6	0.098		
2/PW11/8	3	80%	4.81	462	154 000	0.003		
			4.26	64 064	216 000	0.297		
			3.78	177 944	301 000	0.591	3.93	6.162
			3.34	456 302	426 000	1.073		
			2.56	1.029 x 10^6	893 000	1.152		
			1.73	1.833 x 10^6	2.66 x 10^6	0.689		
			0.82	2.586 x 10^6	21.3 x 10^6	0.122		

TABLE 15. Results of tests with Programmes 6-10 (parallel to constant amplitude S-N curve) on welded specimens of H48

Programme no.	Programme details	Specimen no.	100% stress level tonf/in^2	Endurance programmes	$\Sigma \frac{n}{N}$
5	Complete	2/PW6/1	16.0	306	2.96
		2/PW6/2	15.4	314	2.73
		2/PW6/3	15.0	663	5.39
		2/PW6/4	14.3	529	3.74
		2/PW6/5	13.0	627	3.37
		2/PW6/6	12.0	849	4.10
				Mean	3.72
7	No 100% stress level	2/PW7/1	16.1	246	2.25
		2/PW7/2	15.8	268	2.33
		2/PW7/3	15.8	430	3.73
		2/PW7/4	13.8	345	2.09
		2/PW7/5	11.7	596	2.05
				Mean	2.49
8	No 100% or 90% stress levels	2/PW8/1	15.6	287	2.30
		2/PW8/2	15.0	270	2.02
		2/PW8/3	15.0	302	2.26
		2/PW8/4	13.4	478	2.62
		2/PW8/5	11.9	1 128	4.52
				Mean	2.74
9	No 10% stress level	2/PW9/1	12.0	573	1.67
10	No 10% or 20% stress levels	2/PW10/1	15.1	111	0.47
		2/PW10/2	15.0	168	0.69
		2/PW10/3	12.8	291	0.95
		2/PW10/4	12.8	267	0.71
		2/PW10/5	11.8	625	1.31
				Mean	0.83



Note: Numbers by the welds show welding sequence, numbers in brackets are for the reverse side.

b)

Fig.1. Details of specimens. a) Notched. b) Welded.

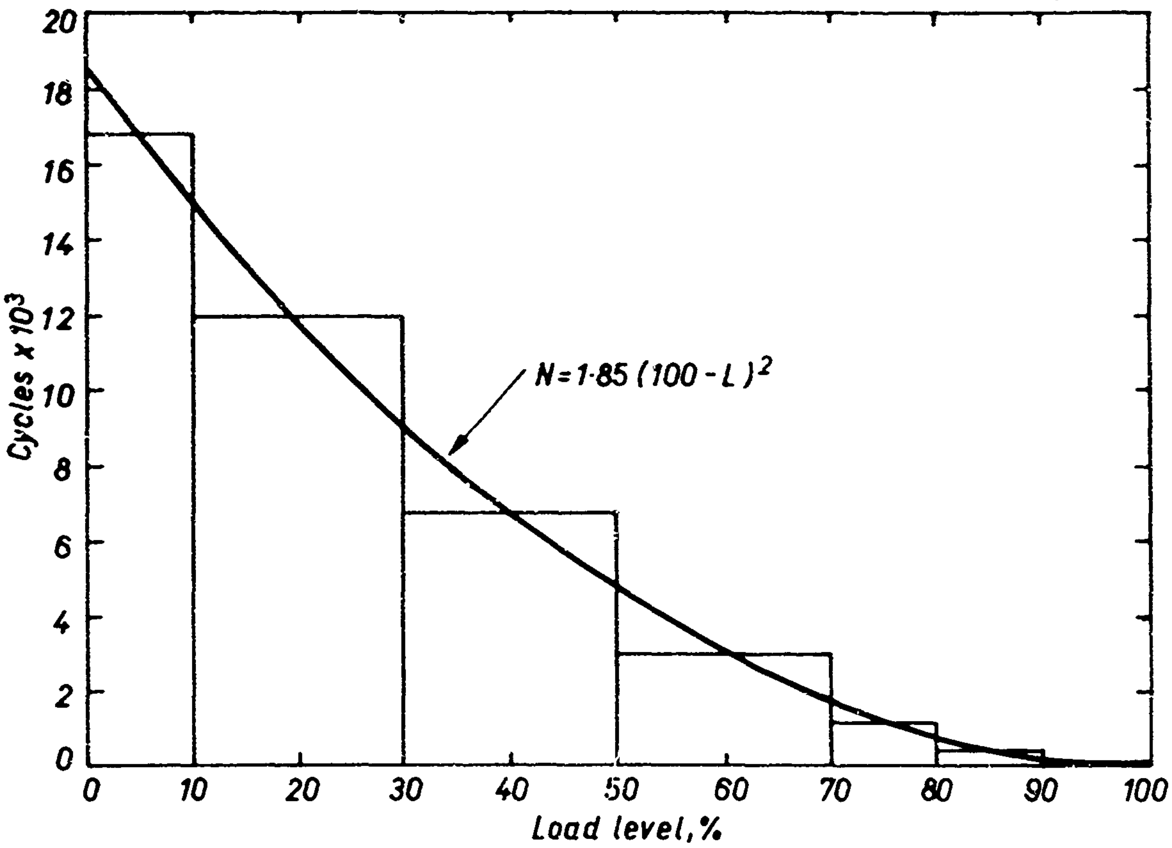


Fig.2. Quadratic spectrum on which programmes 1 to 5 and 7 were based.

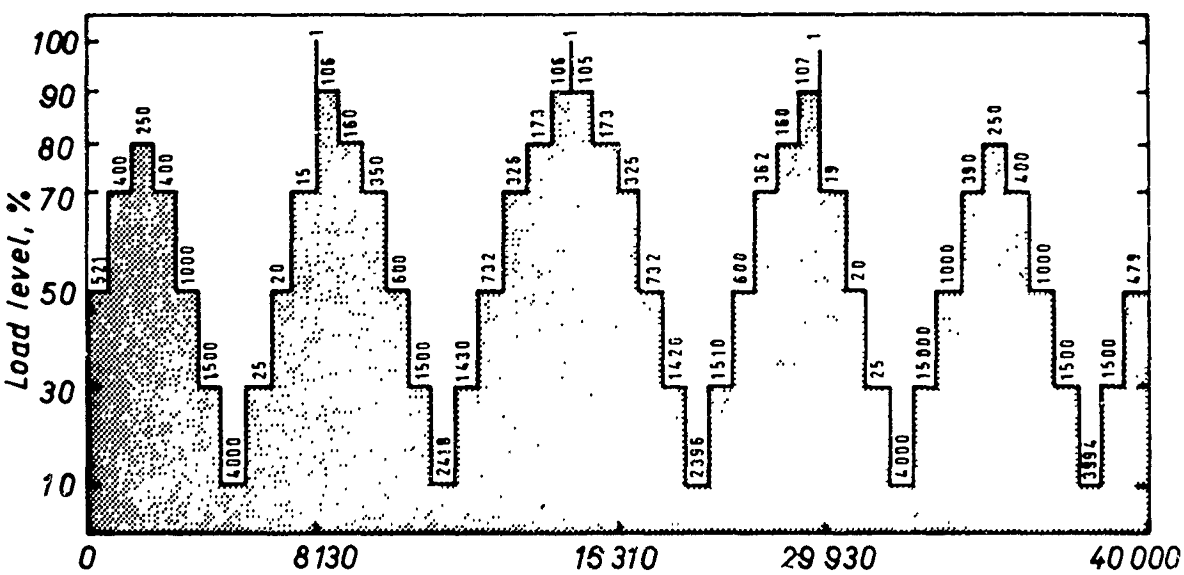
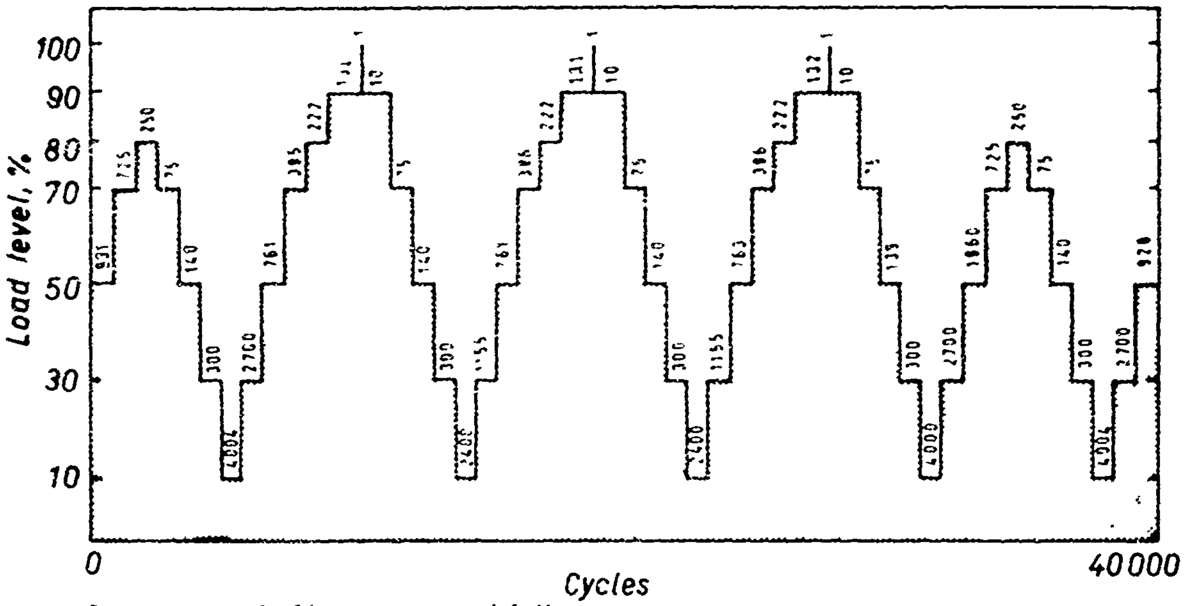
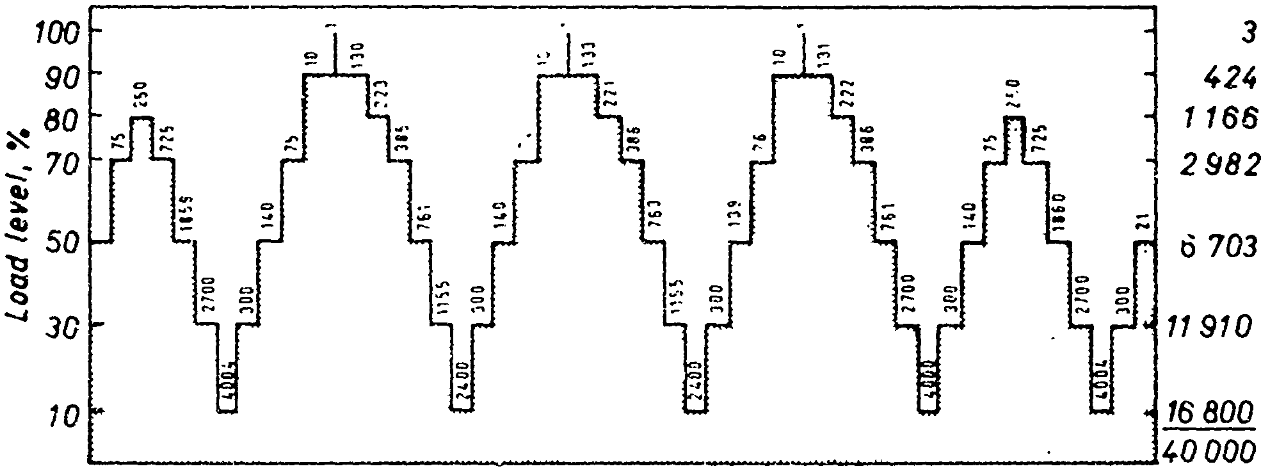


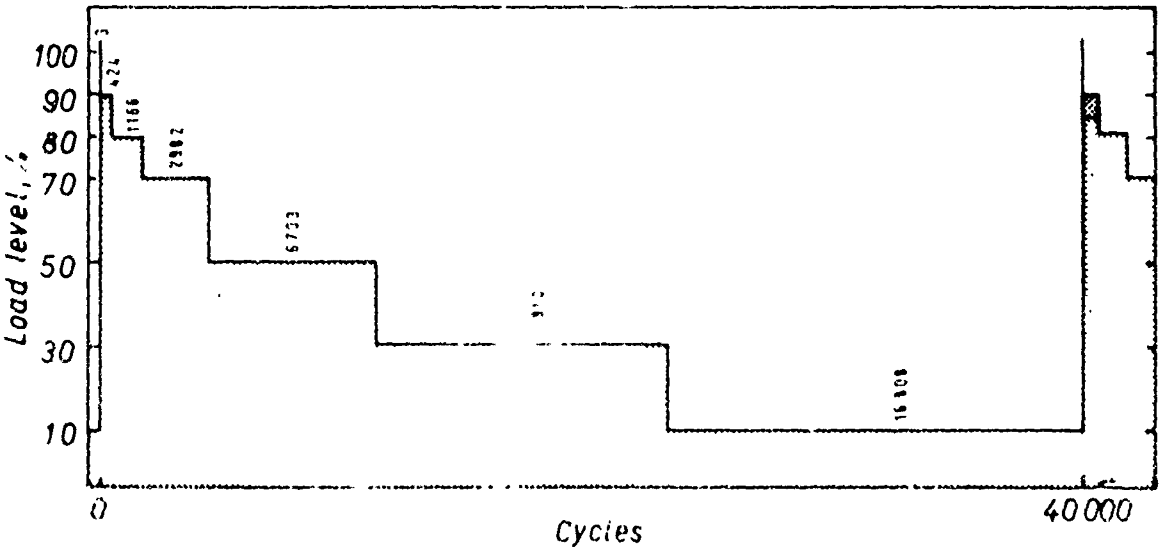
Fig.3. Programme 1.



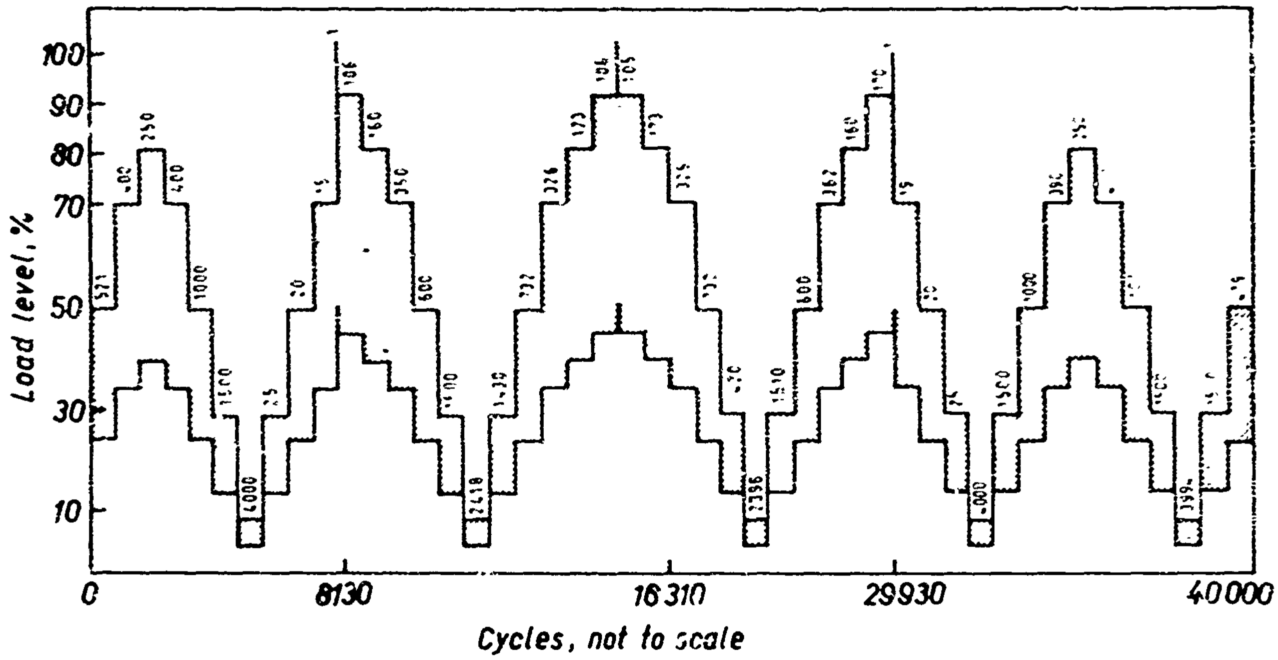
Programme 2. Slow rise, rapid fall.



Programme 3. Rapid rise, slow fall



Programme 4 Rapid rise, slow fall with one peak (Programme 5. Slow rise, rapid fall with one peak, is identical but with the ordering of the blocks reversed)



F g.5a. P ogramme 1, half tensile (R = 0.5) loading

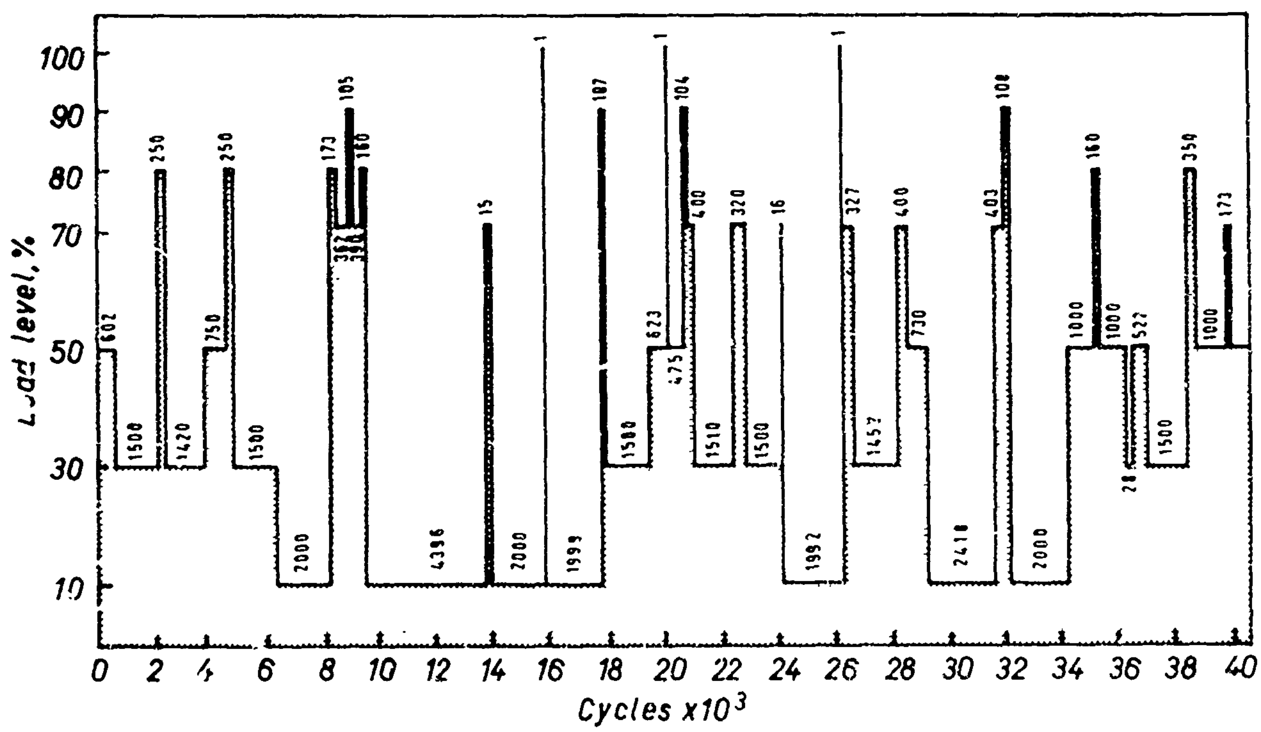


Fig.5b. Randomised programme (Programme 11)

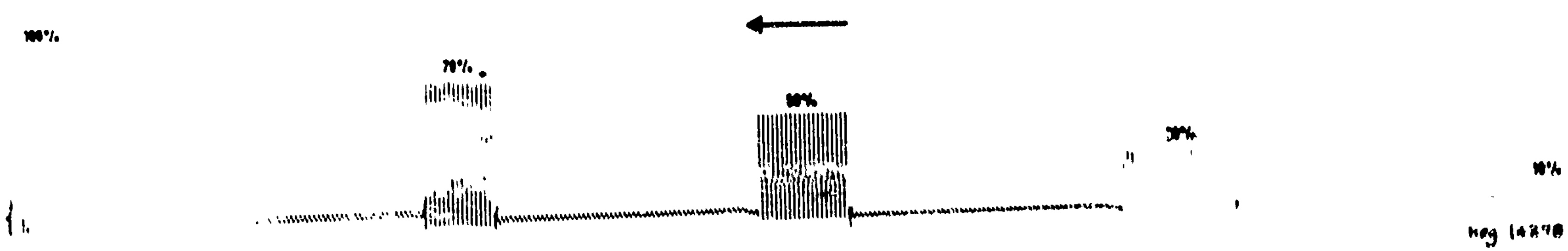


Fig.6. Strain gauge record showing a section of a programmed test.

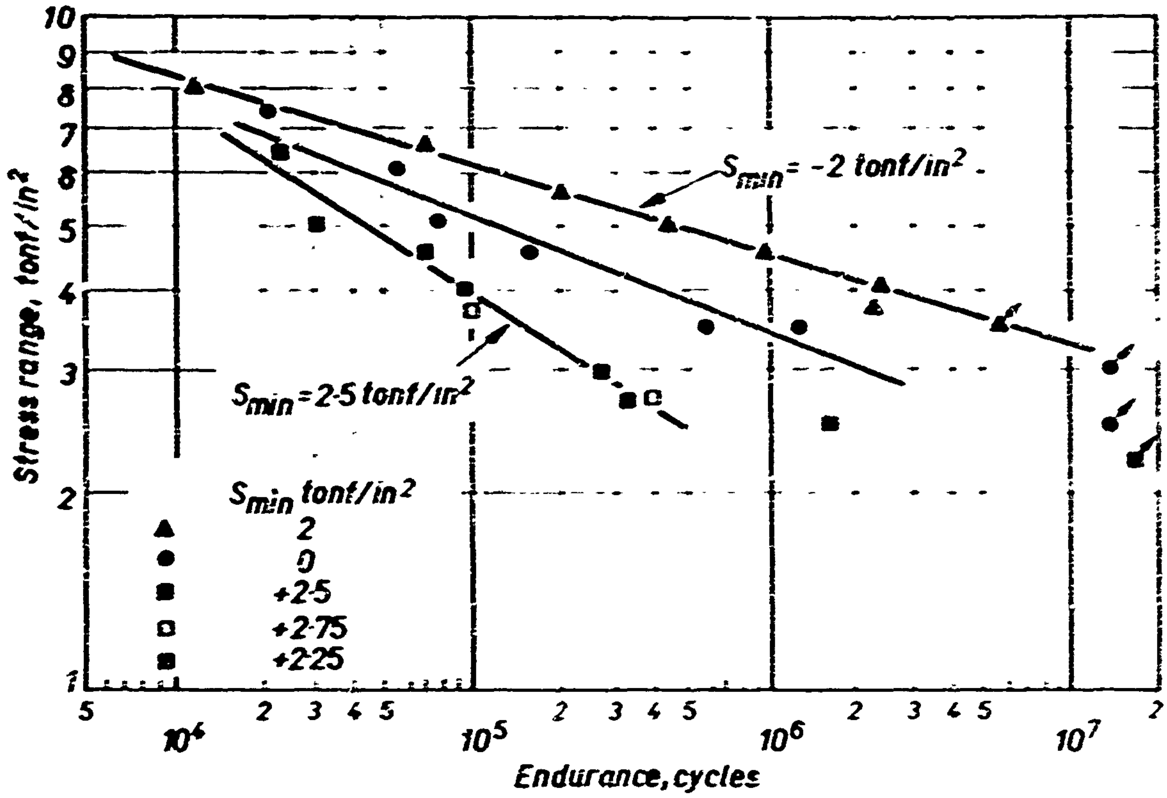


Fig.7. Results of constant amplitude tests on notched specimens of D74S.

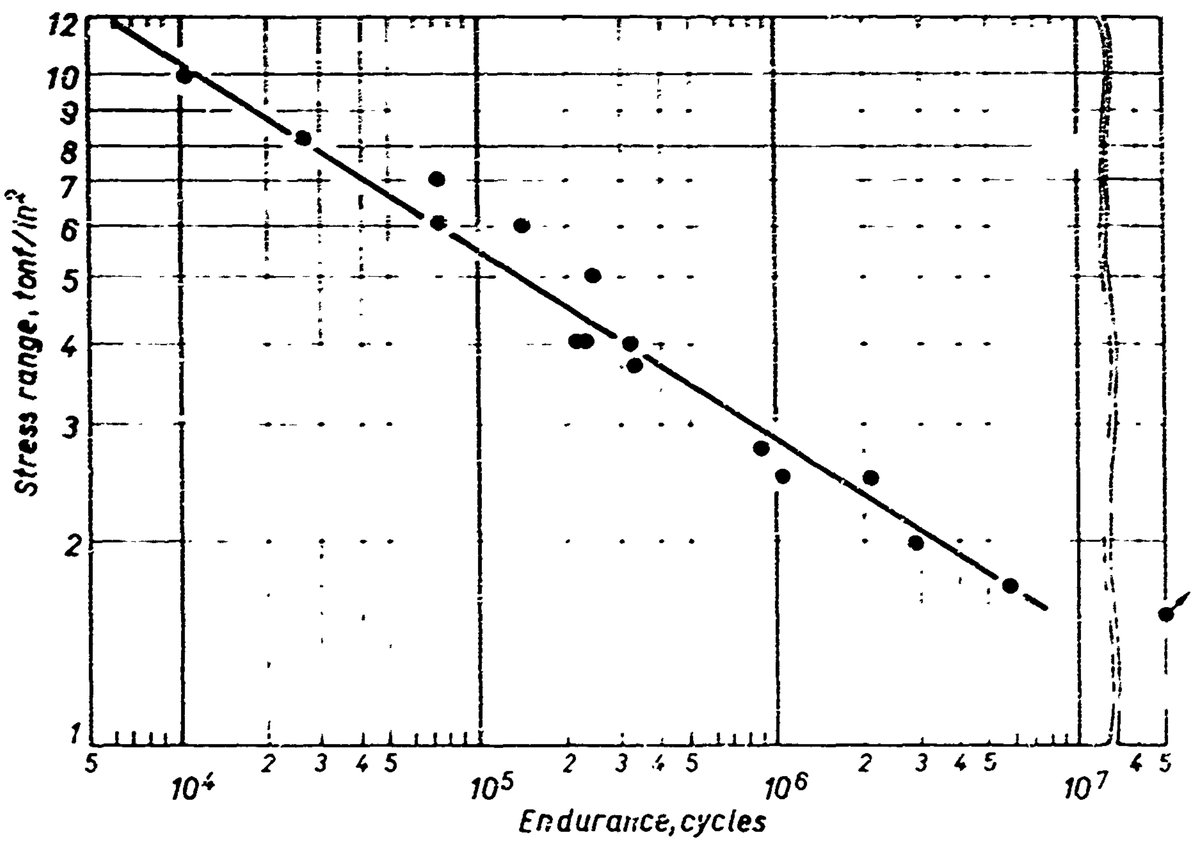


Fig.8. Results of constant amplitude tests under [illegible]

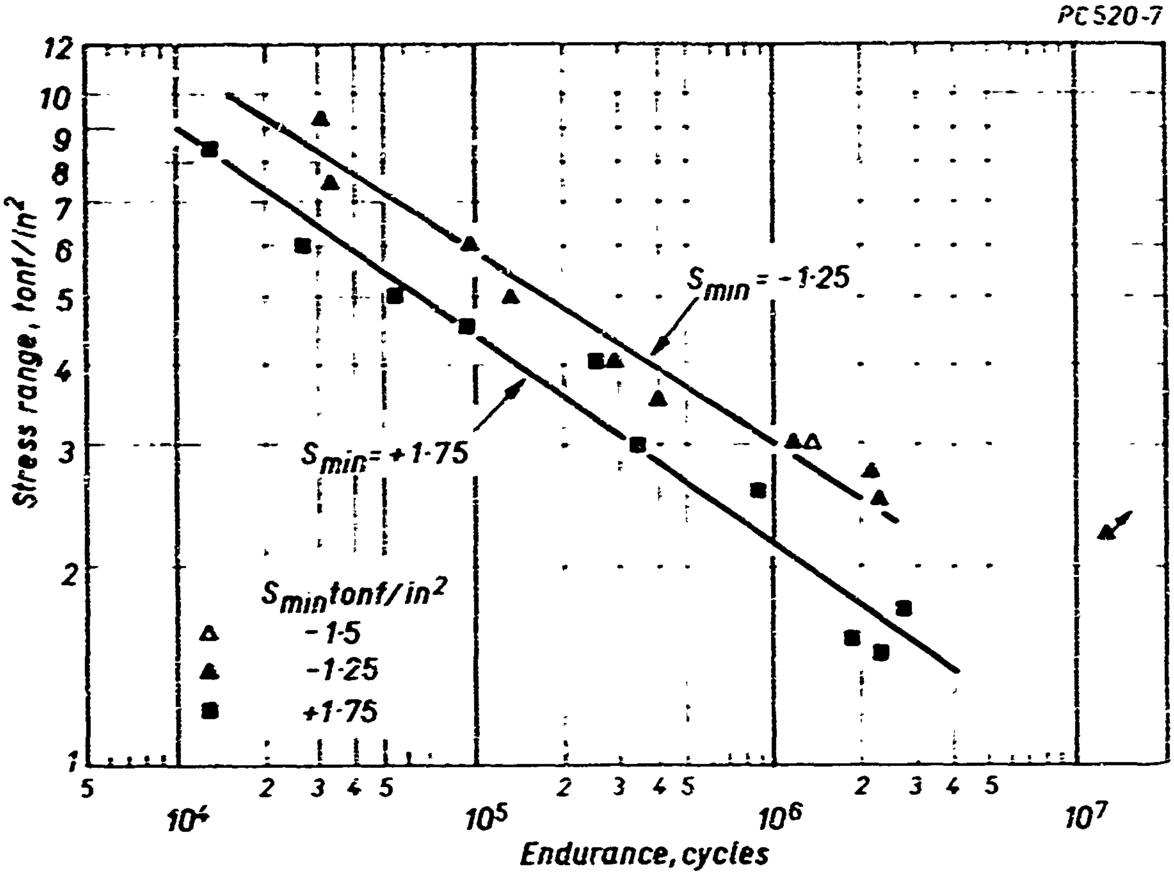


Fig.9. Results of constant amplitude tests on welded specimens of D74S.

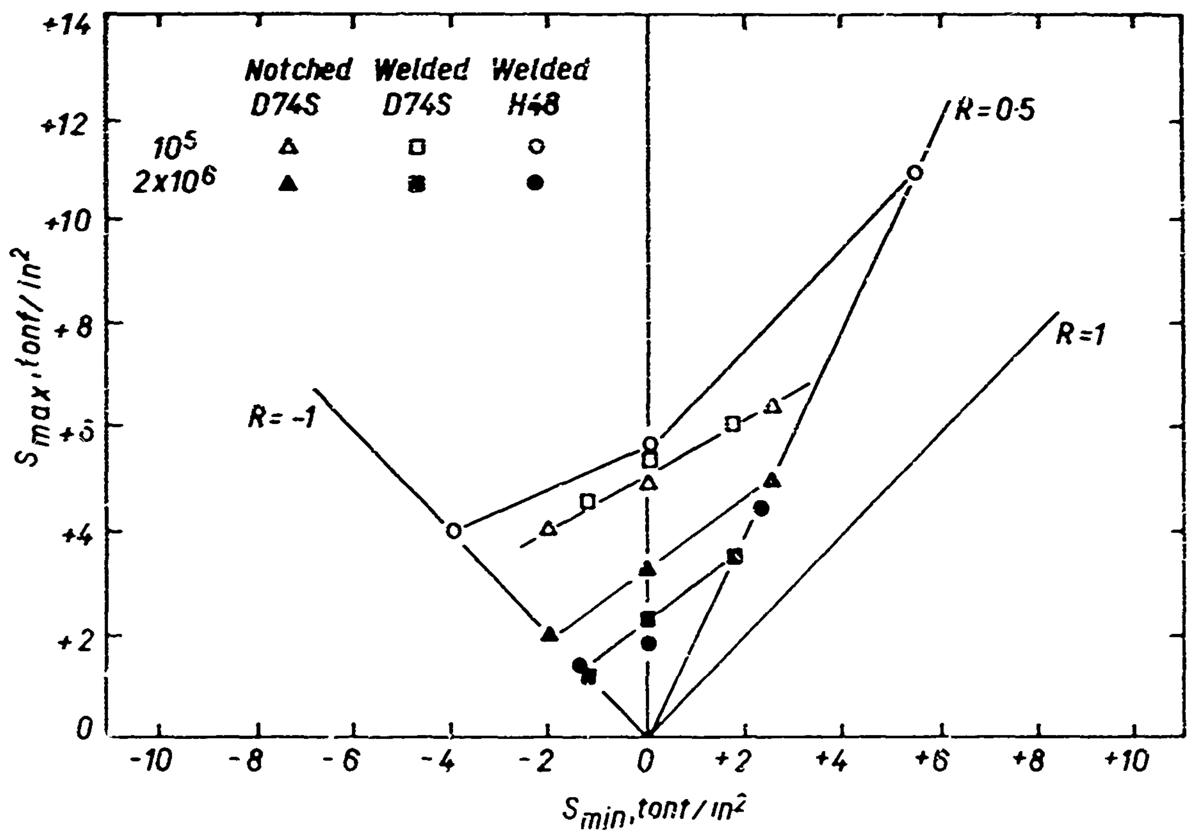
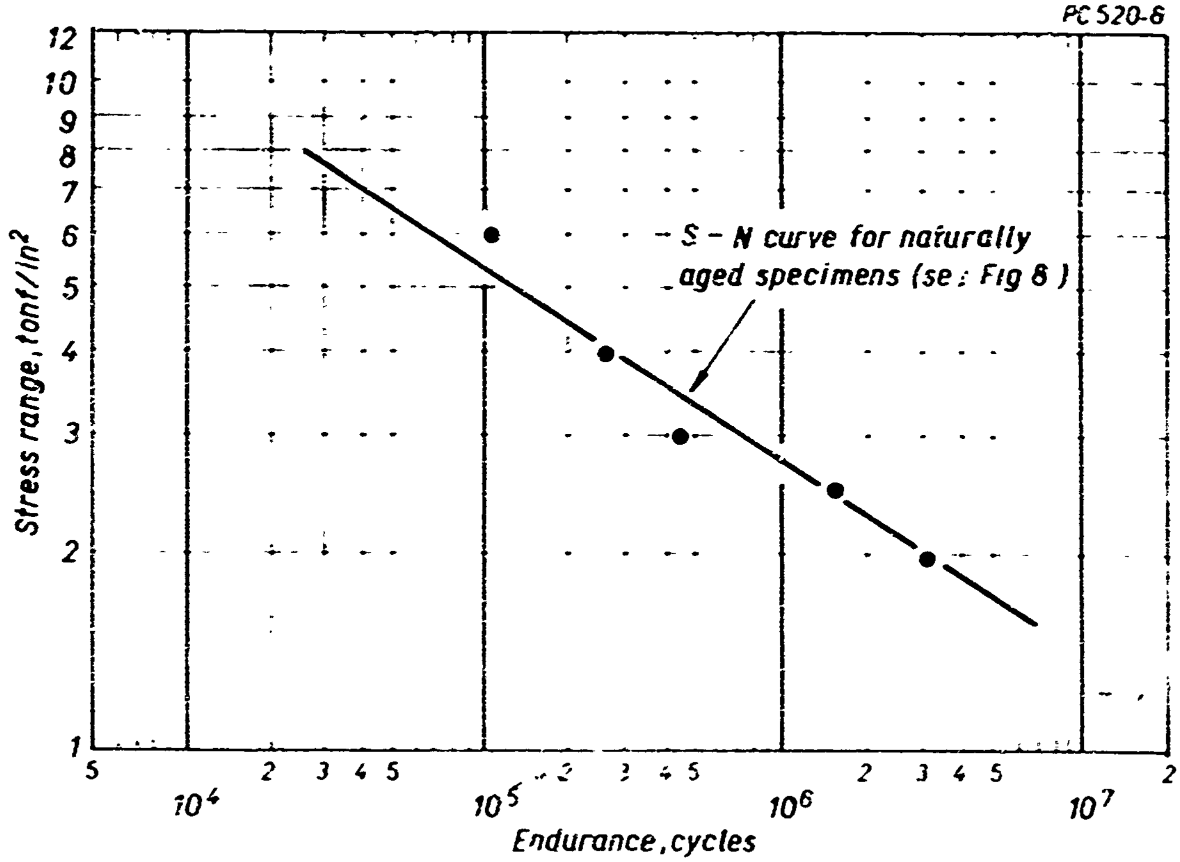
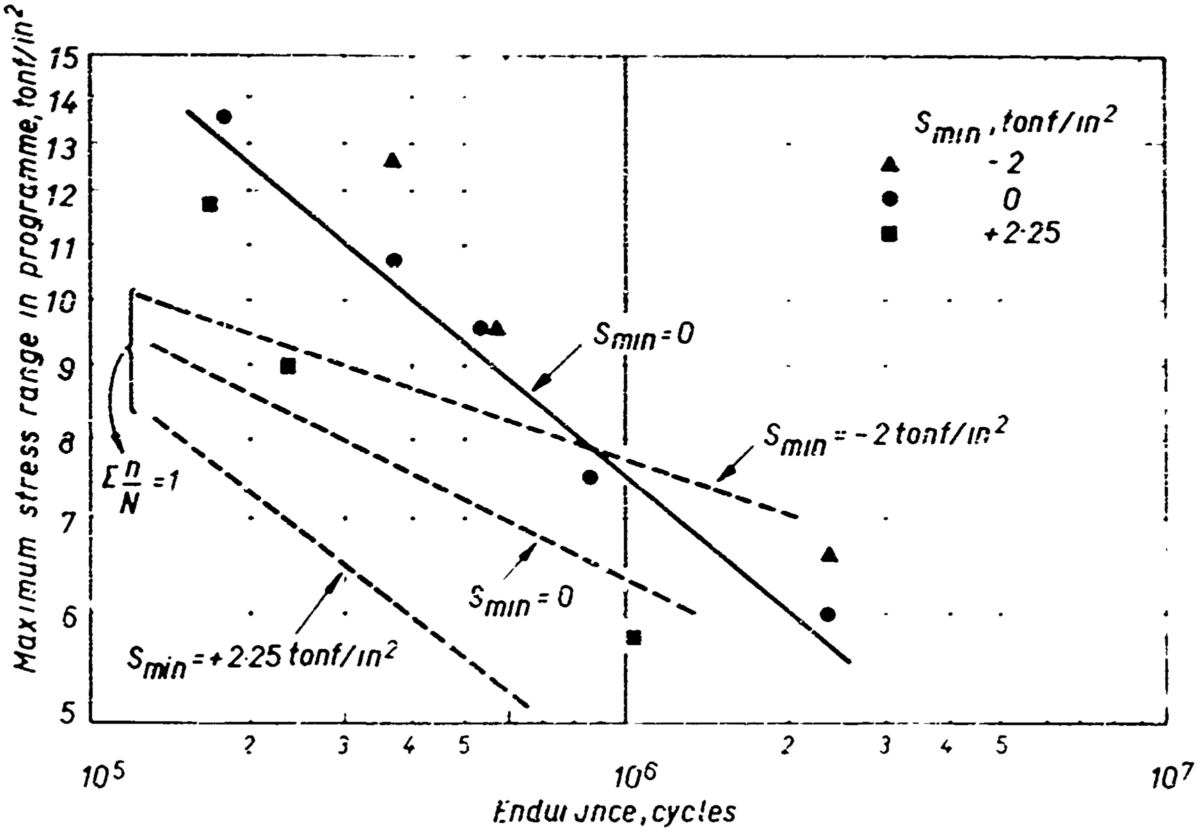


Fig.10. Modified Goodman diagram for constant amplitude notched and welded D74S and welded H48.


PC 520-6
Stress range, tonf/in²
Endurance, cycles
S – N curve for naturally aged specimens (see Fig 8)
10⁴
10⁵
10⁶
10⁷


Maximum stress range in programme, tonf/in²
Endurance, cycles
Smin, tonf/in²
- 2
0
+2·25
Smin = 0
Smin = -2 tonf/in²
Smin = 0
Smin = +2·25 tonf/in²
Σ n/N = 1
10⁵
10⁶
10⁷

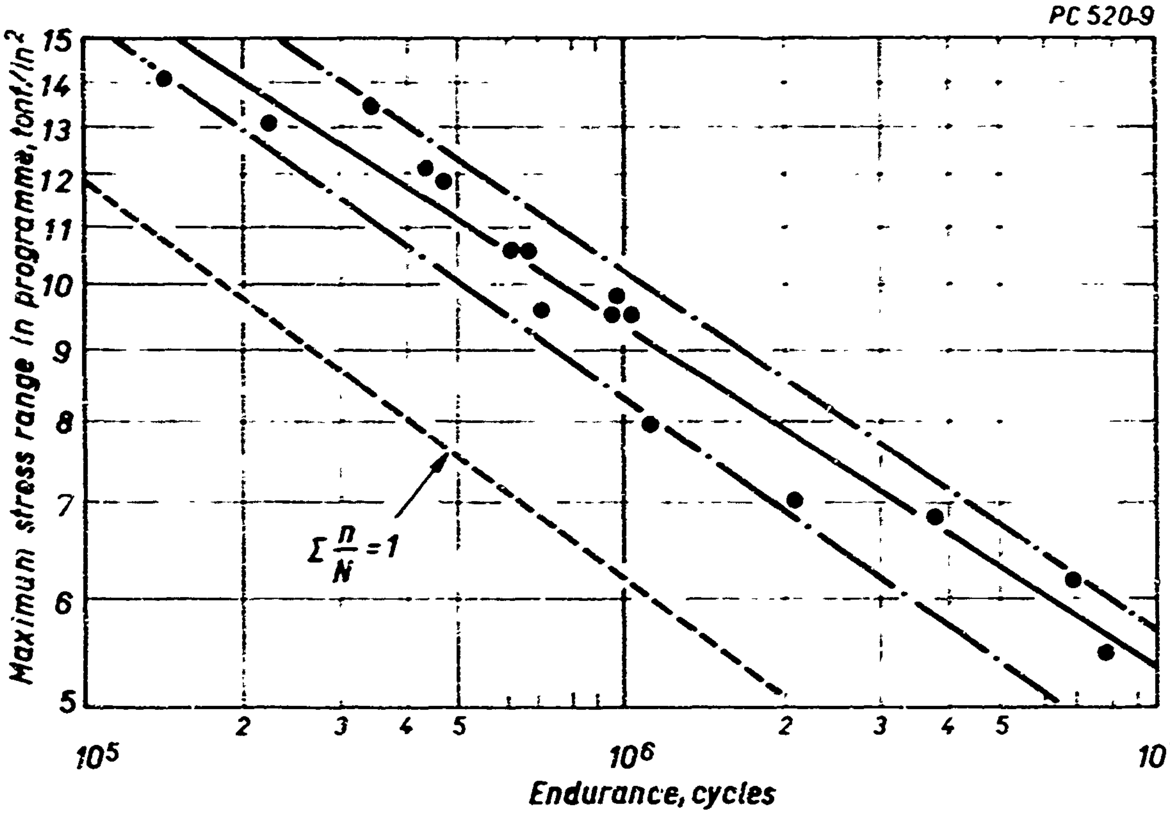


Fig. 13. Results of programmed fatigue tests (Programme 1 $S_{min} = 0$) on welded specimens of D74S.

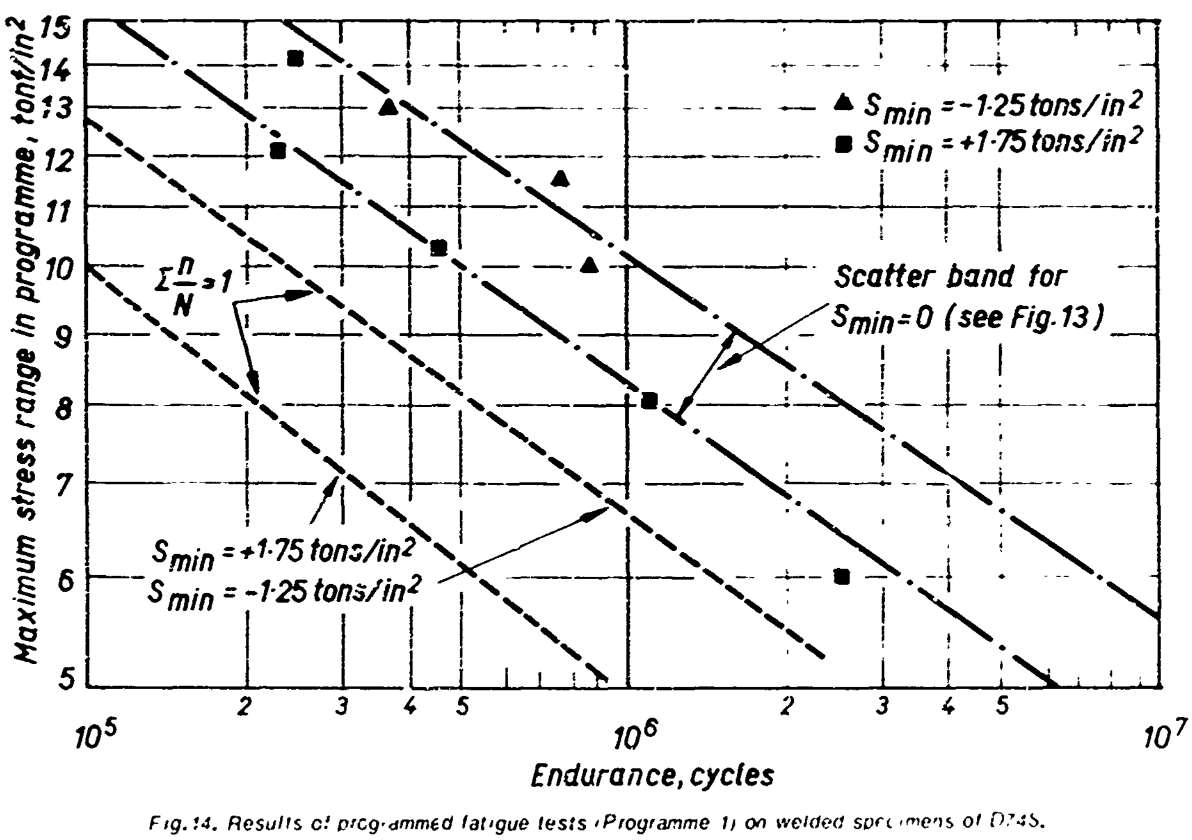


Fig. 14. Results of programmed fatigue tests (Programme 1) on welded specimens of D74S.

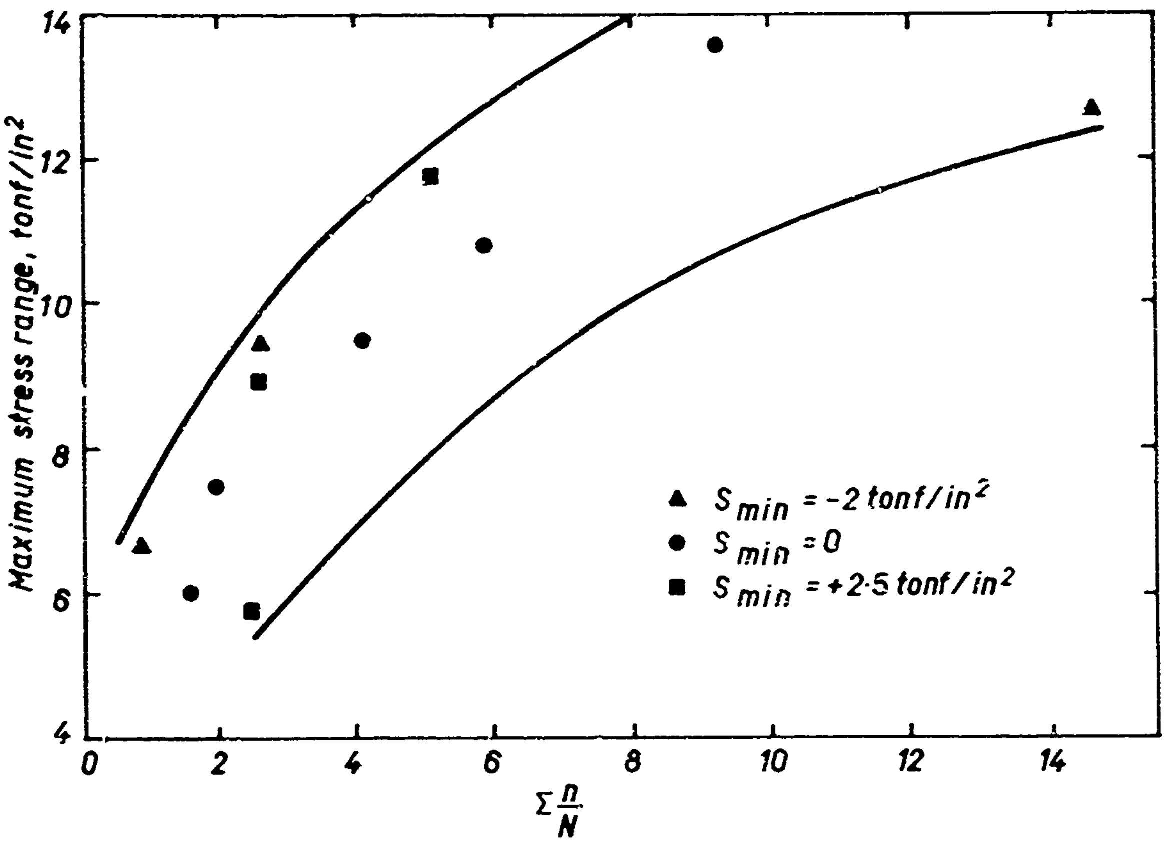


Fig. 15. $\Sigma\frac{n}{N}$ plotted against maximum stress range for notched specimens.

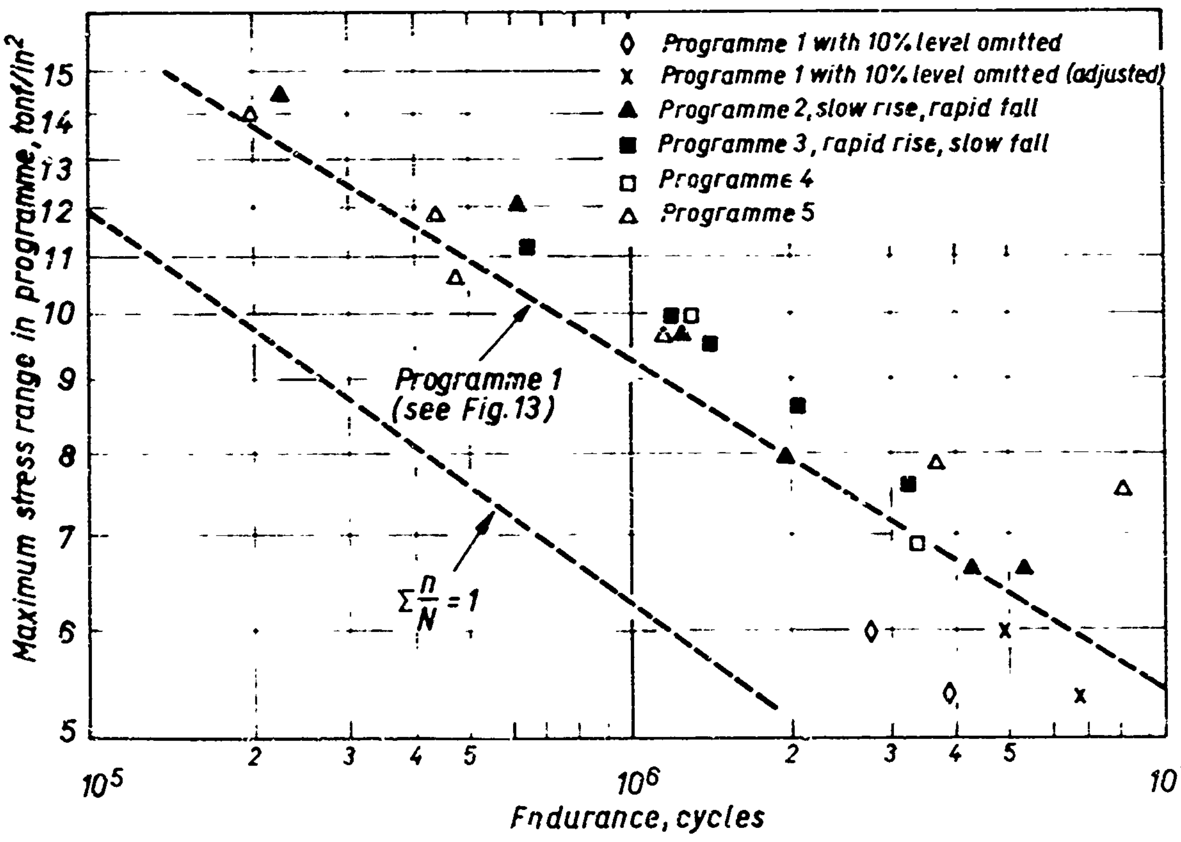


Fig. 16. Results of programmed fatigue tests under pulsating tensile loading on welded specimens of [illegible]

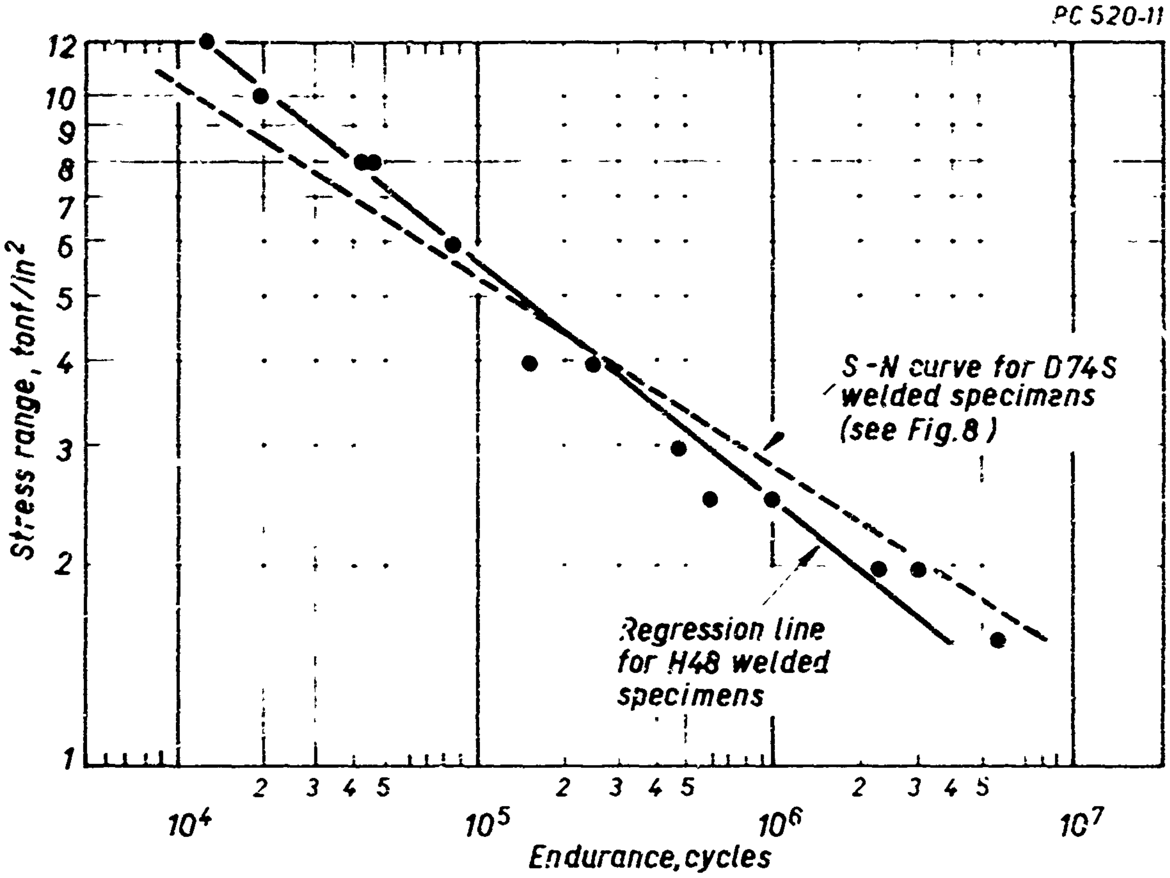


Fig. 17. Results of constant amplitude tests on welded specimens of H48 pulsating tension loading.

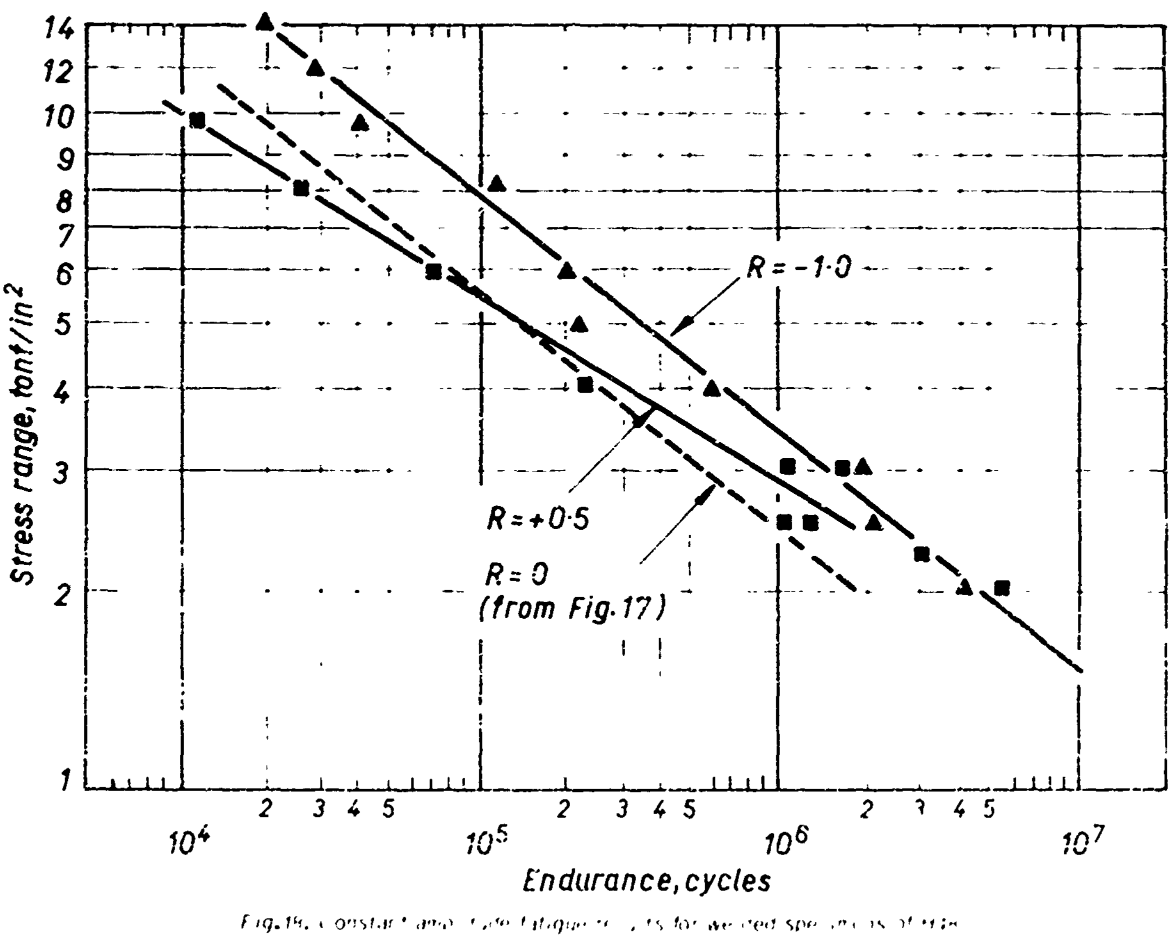


Fig. 18. Constant amplitude fatigue [illegible] for welded specimens of H48

PC 520-12

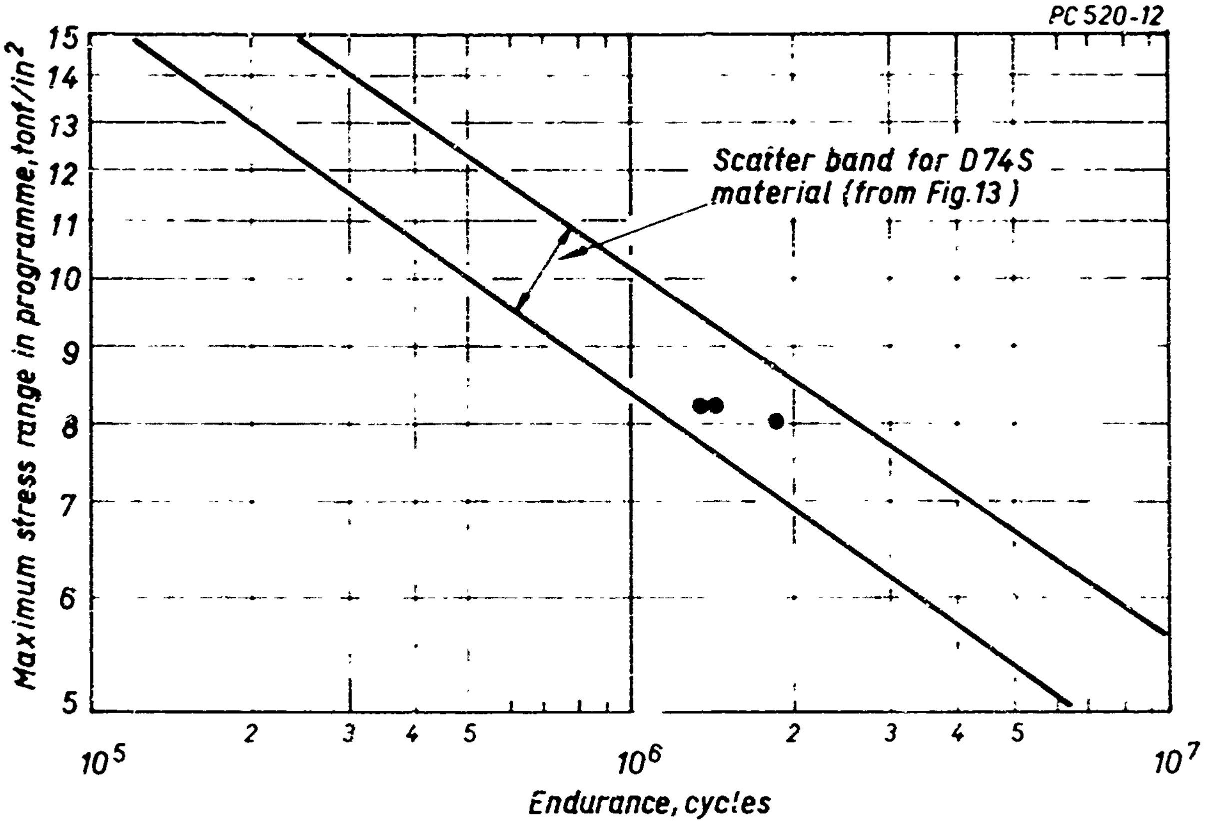


Fig.19. Resu[illegible]ts of programmed fatigued tests. Progra[illegible]me 1, R [illegible] 0, on welded specimens of H4[illegible].

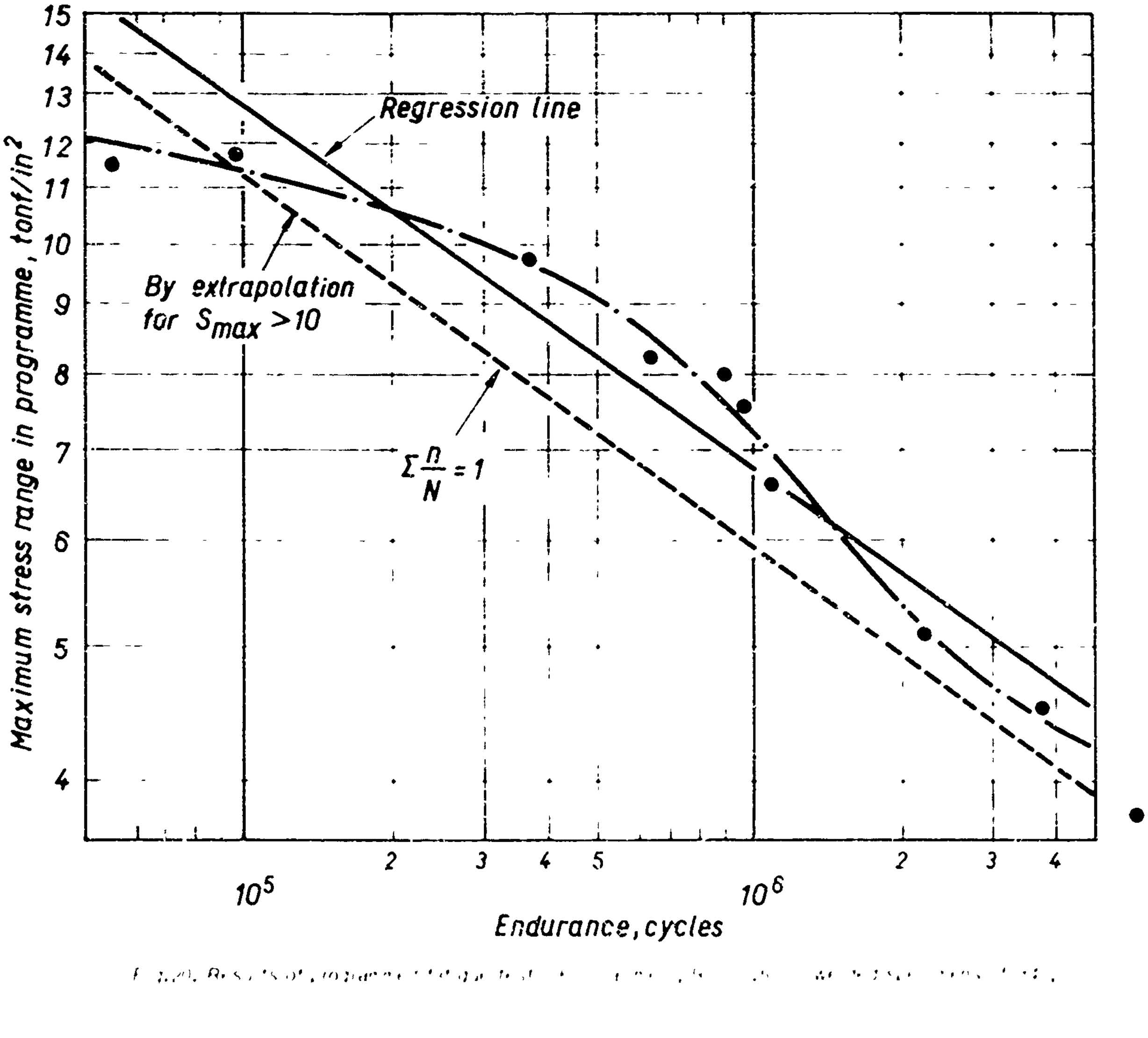


Fig.20. Res[illegible]ts of programmed fatigue tests [illegible]

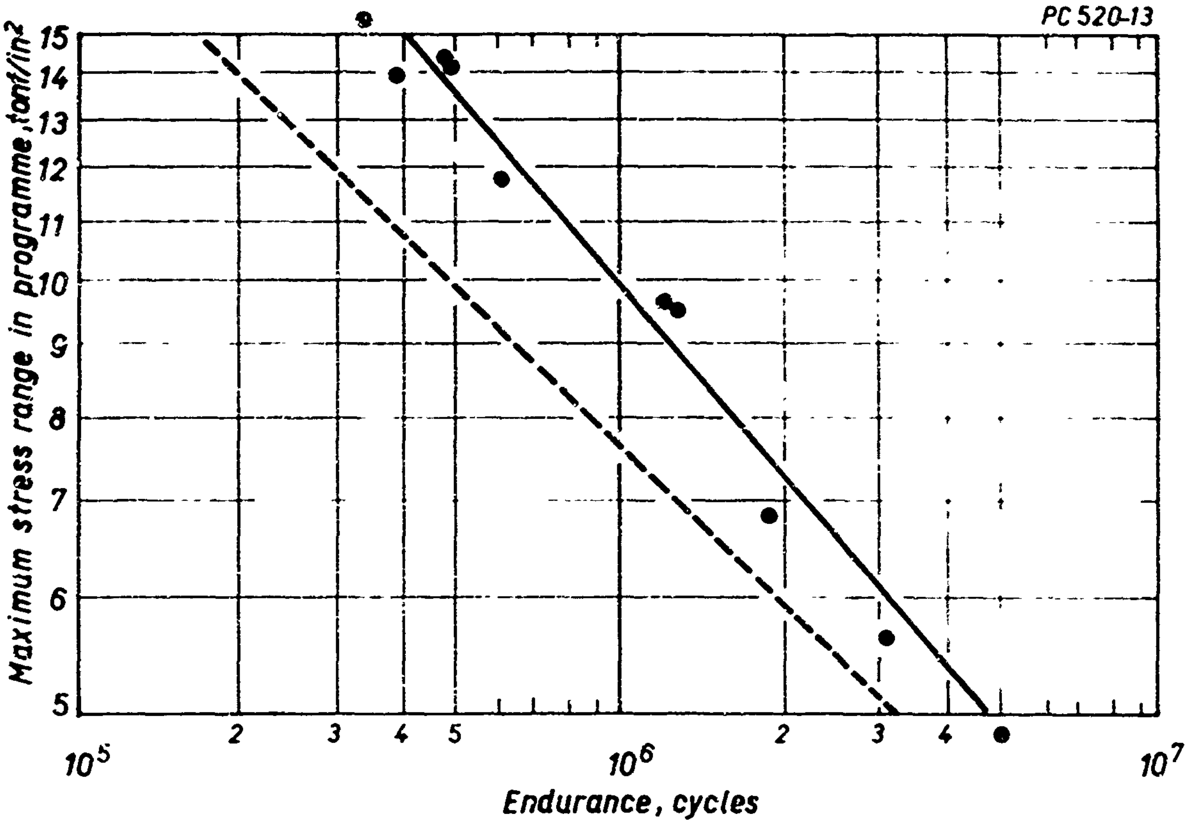


Fig.21. Results of programmed fatigue tests (Programme 1, R = -1) on welded specimens of H48.

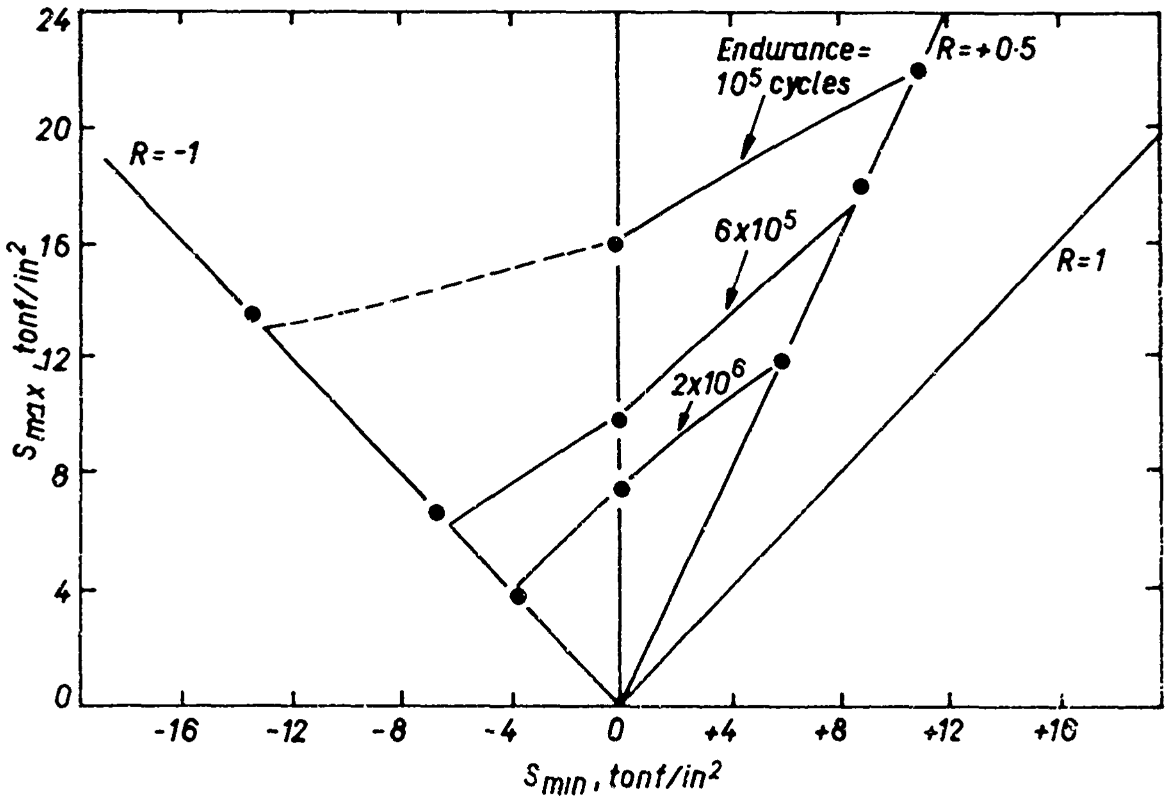


Fig.22. Results of programmed tests on welded H48 material for different values of R in the form of a modified Goodman diagram.

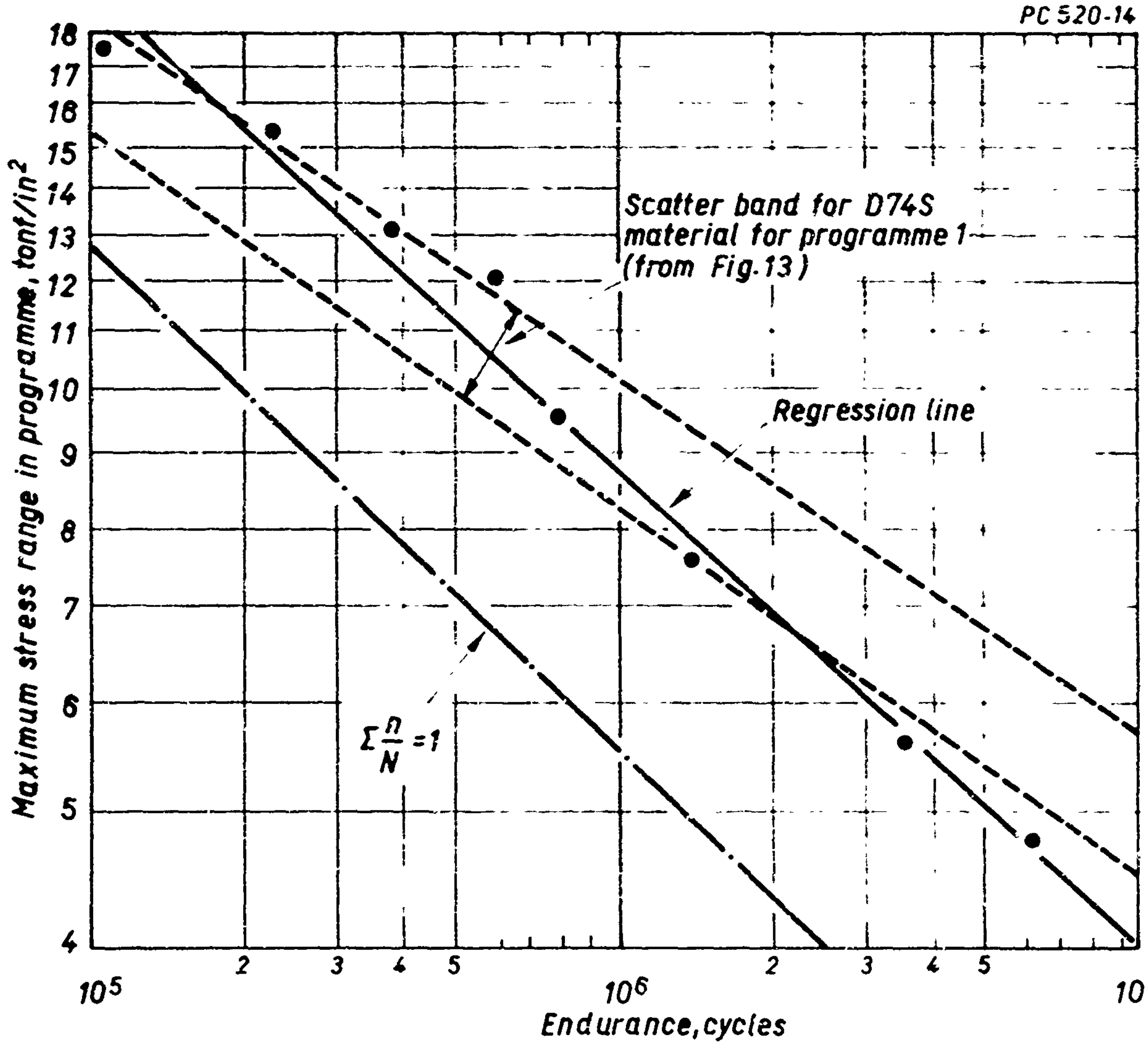


Fig.23. Results of randomised programme fatigue tests (Programme 11, R = 0) on welded specimens of H48.

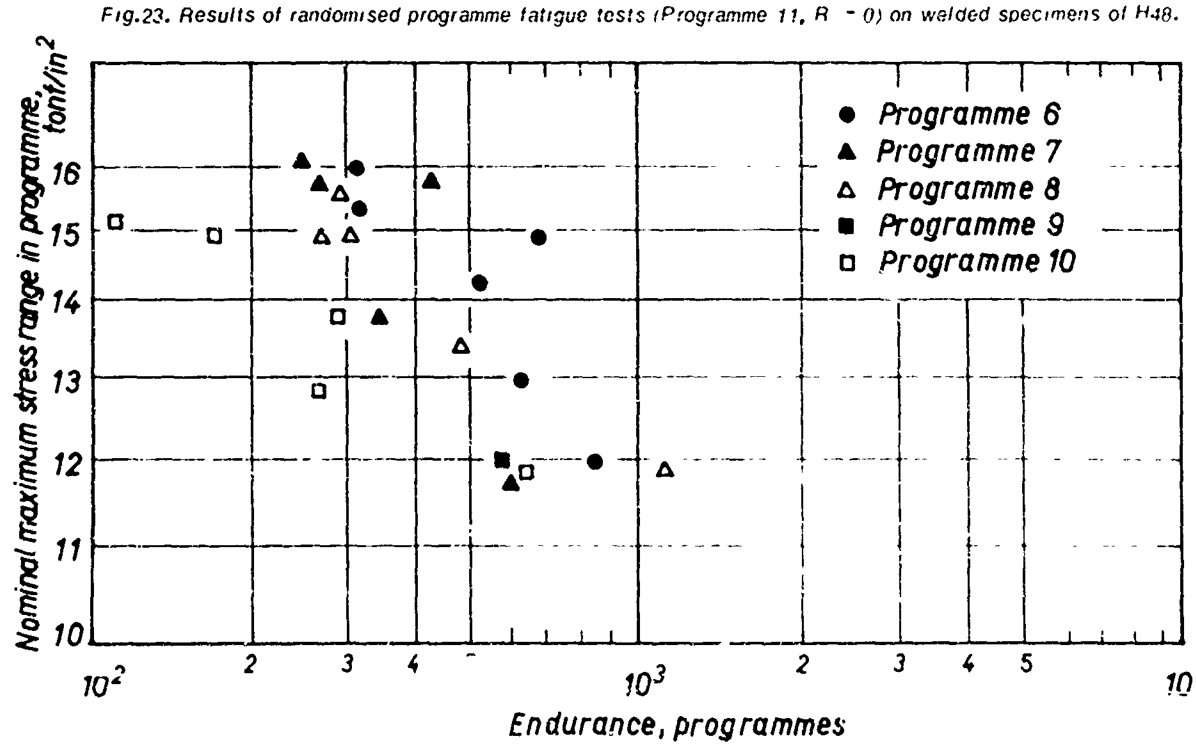


Fig.24. Results of programmed fatigue tests using spectrum parallel to the constant amplitude S-N curve (Programmes 6, 7, 8, 9 and 10) on welded specimens of H48.

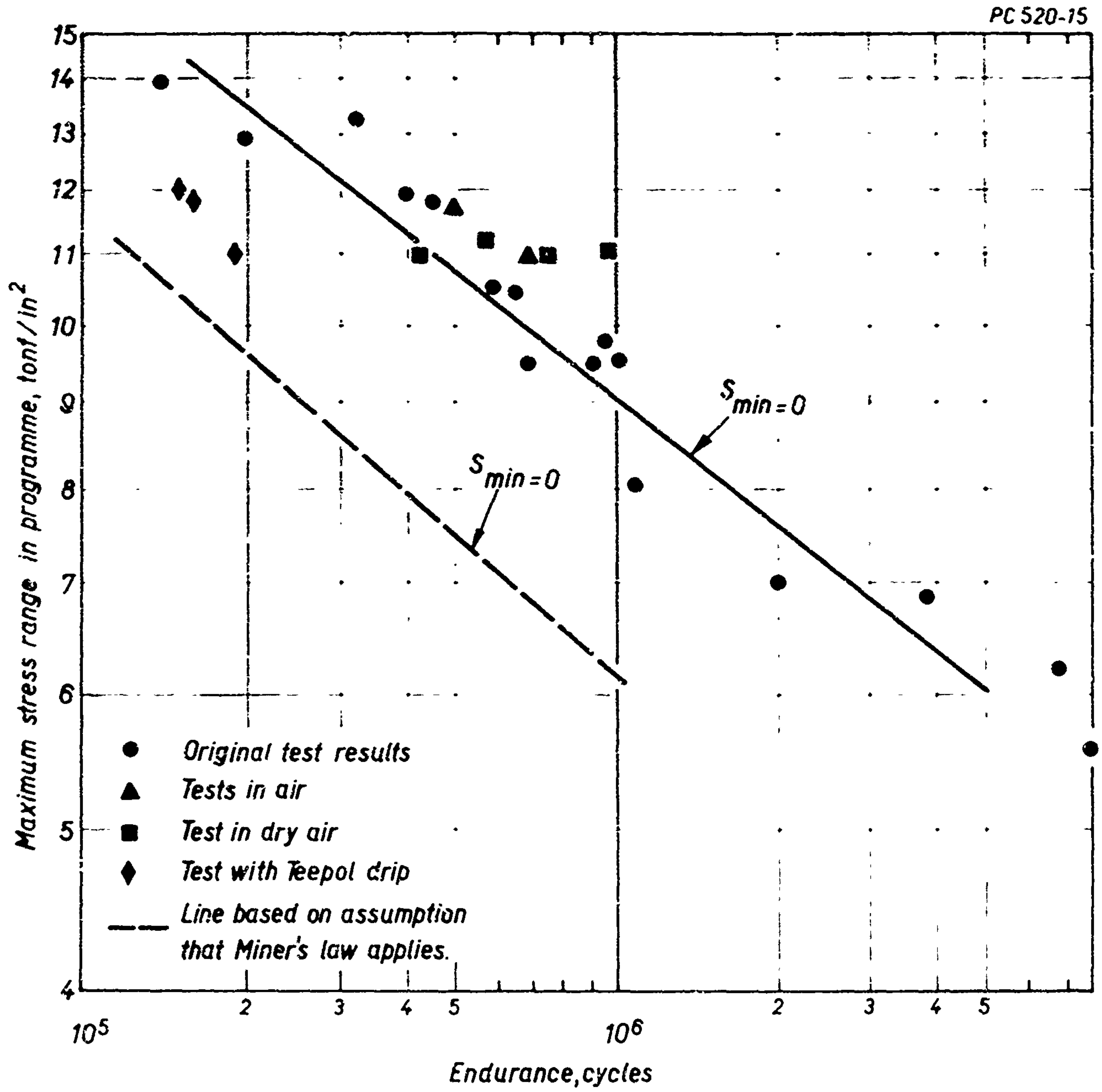


Fig.A1. Results of programmed fatigued tests on welded specimens showing effects of Teepol drip.

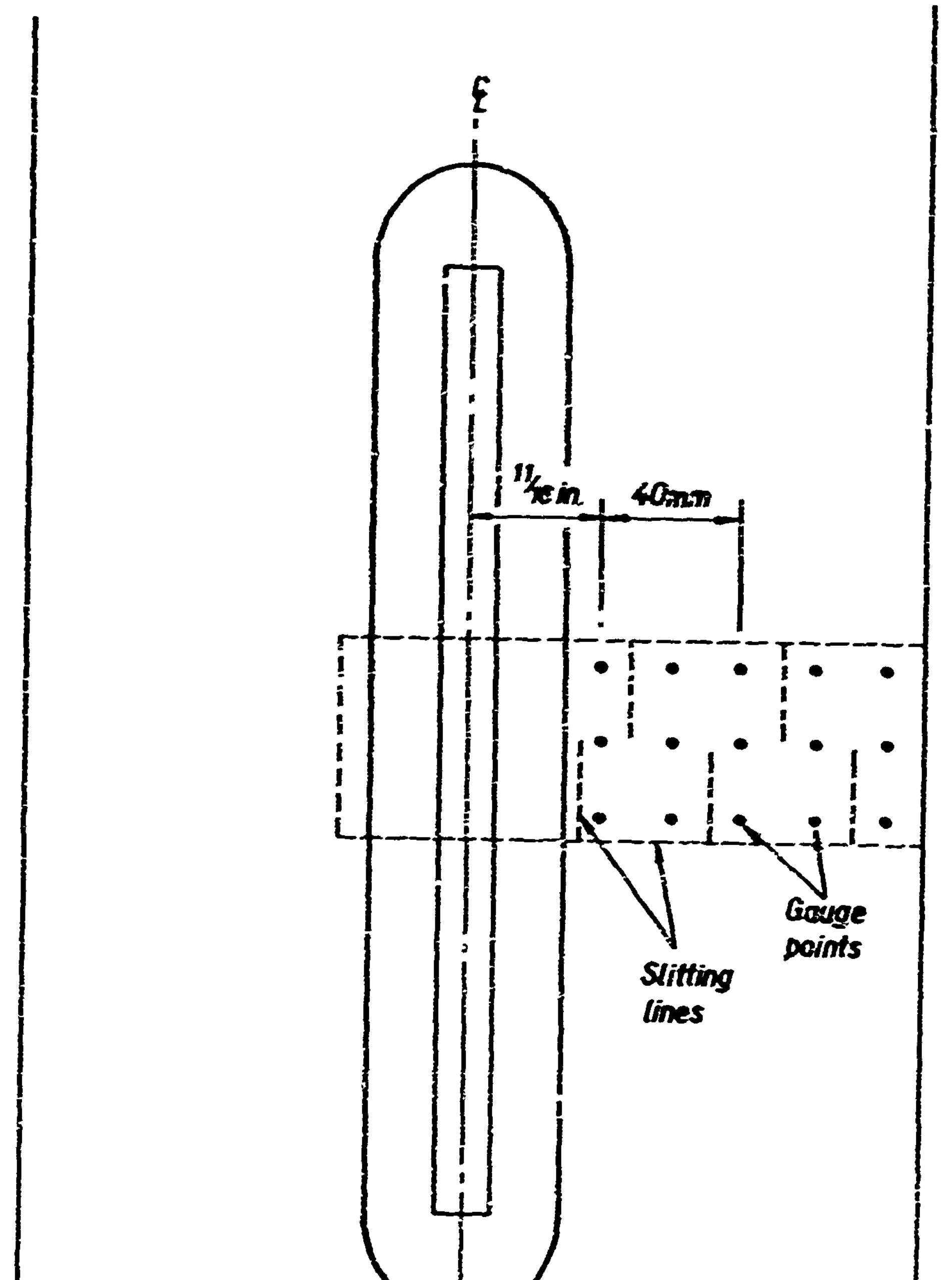


Fig.B1. Arrangement of gauge lengths for residual stress measurements.

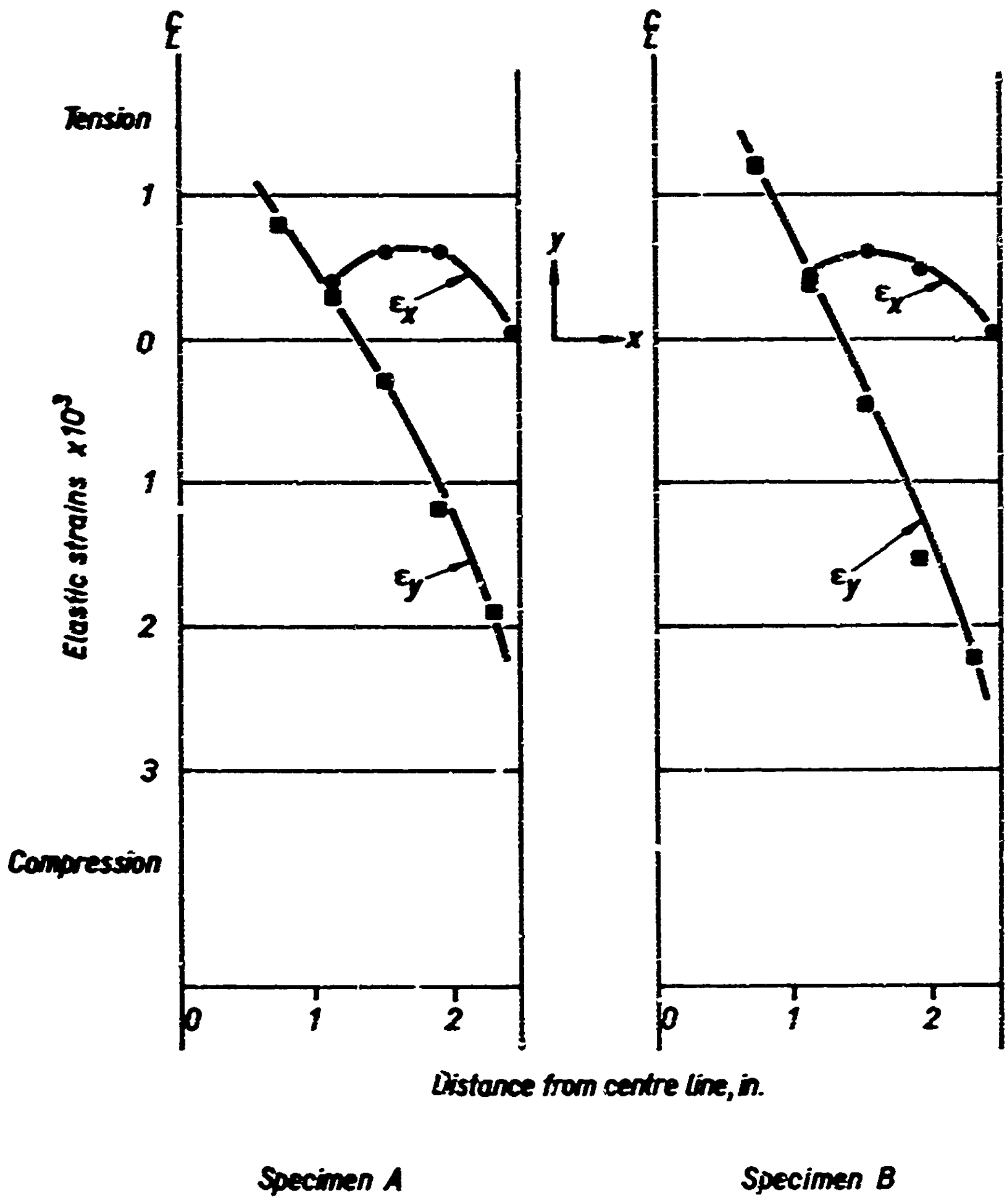


Fig.B2. Residual strains measured by relaxation.

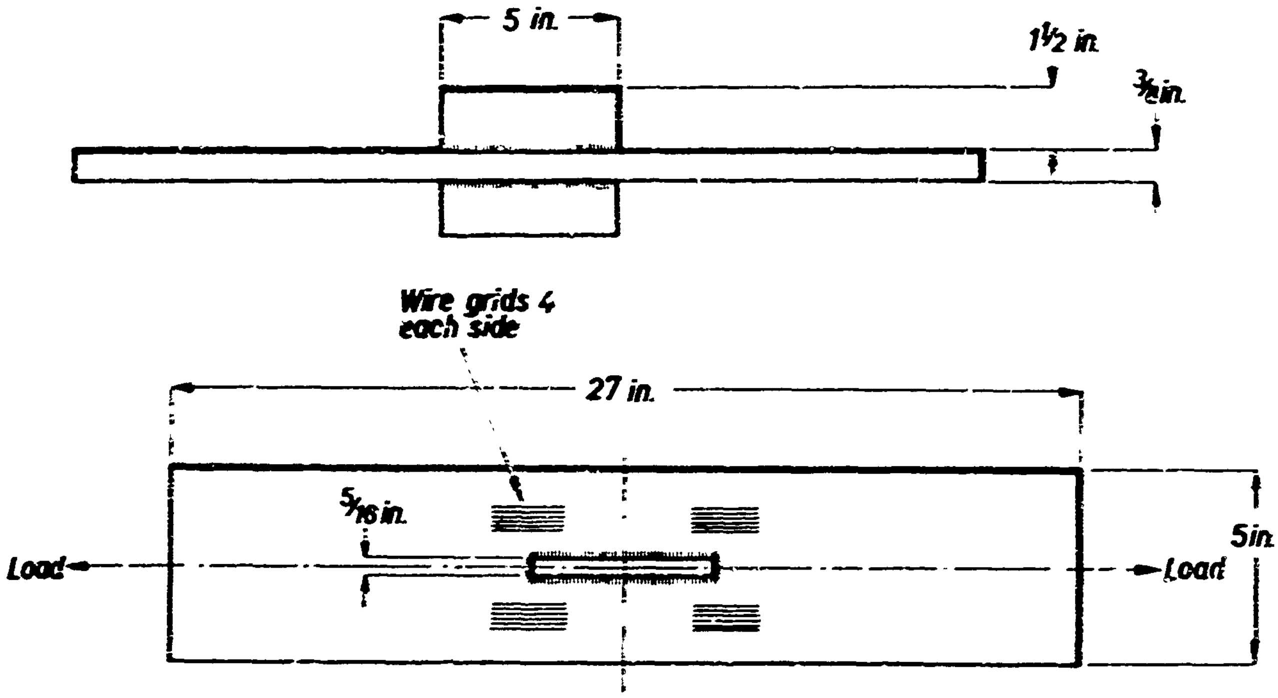


Fig.C1. Welded Al:Zn:Mg specimens showing positions of crack propagation grids.

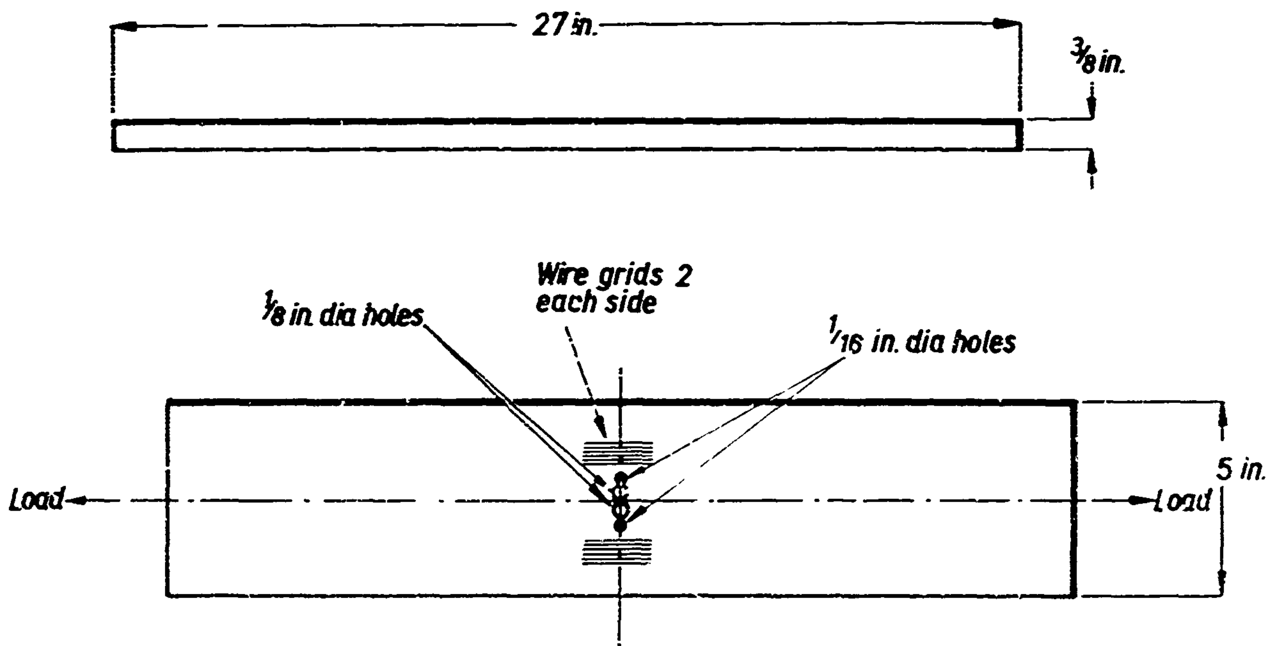


Fig.C2. Notched Al:Zn:Mg specimens showing positions of crack propagation grids.

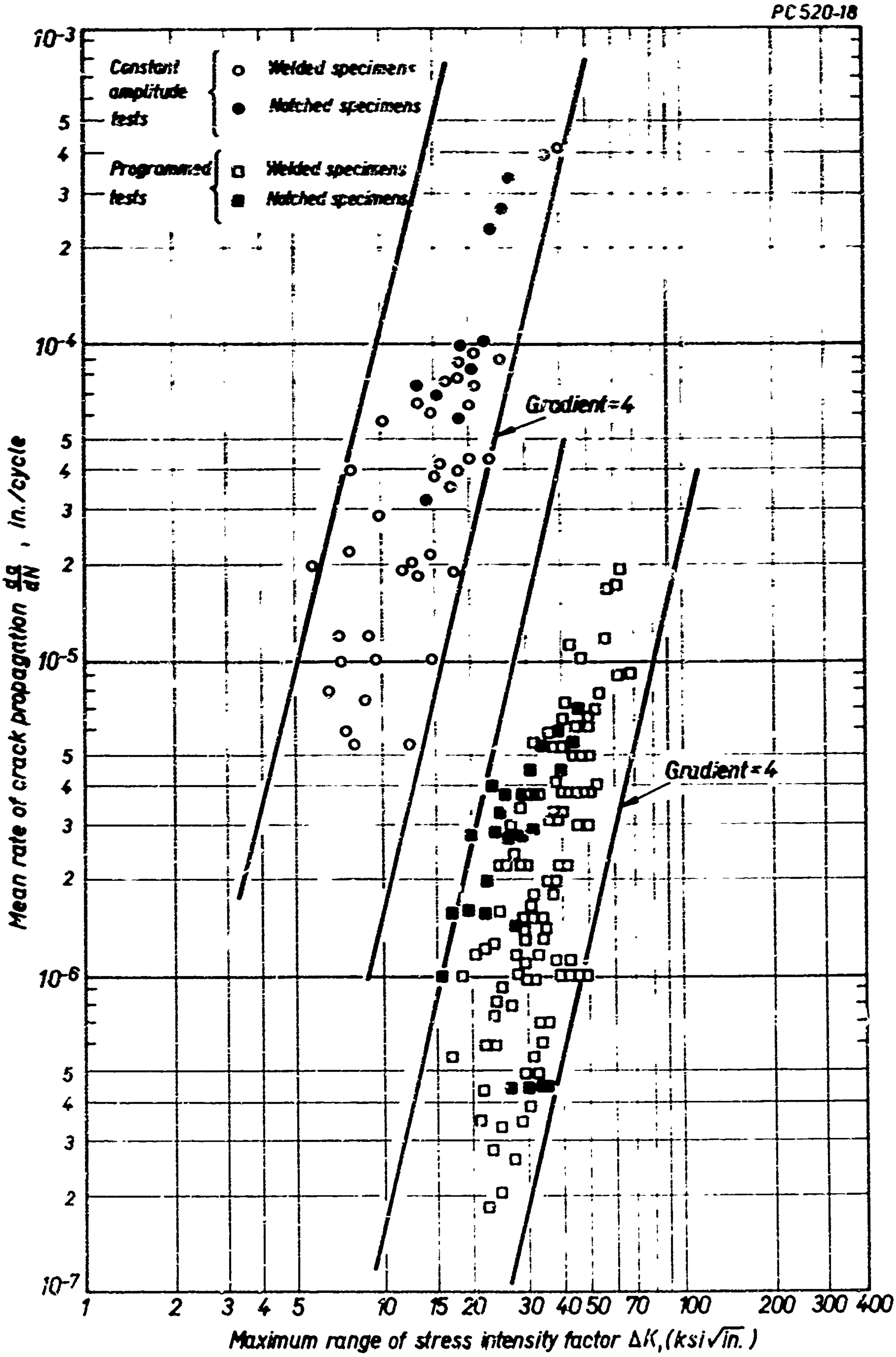


Fig.C3. Plot of log $\frac{da}{dN}$ V log ΔK for all specimens.

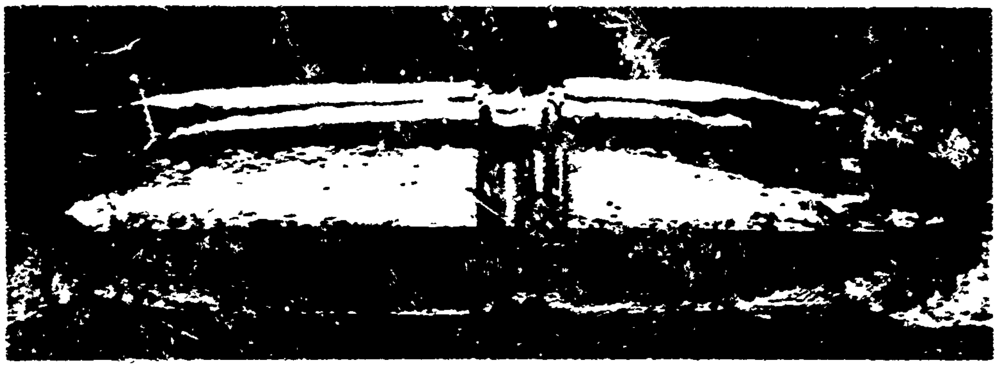


Fig.C4. Fracture surface of notched fatigue specimen tested under constant amplitude loading.

Fig.C5. Fracture surface of welded fatigue specimen tested under programmed loading.

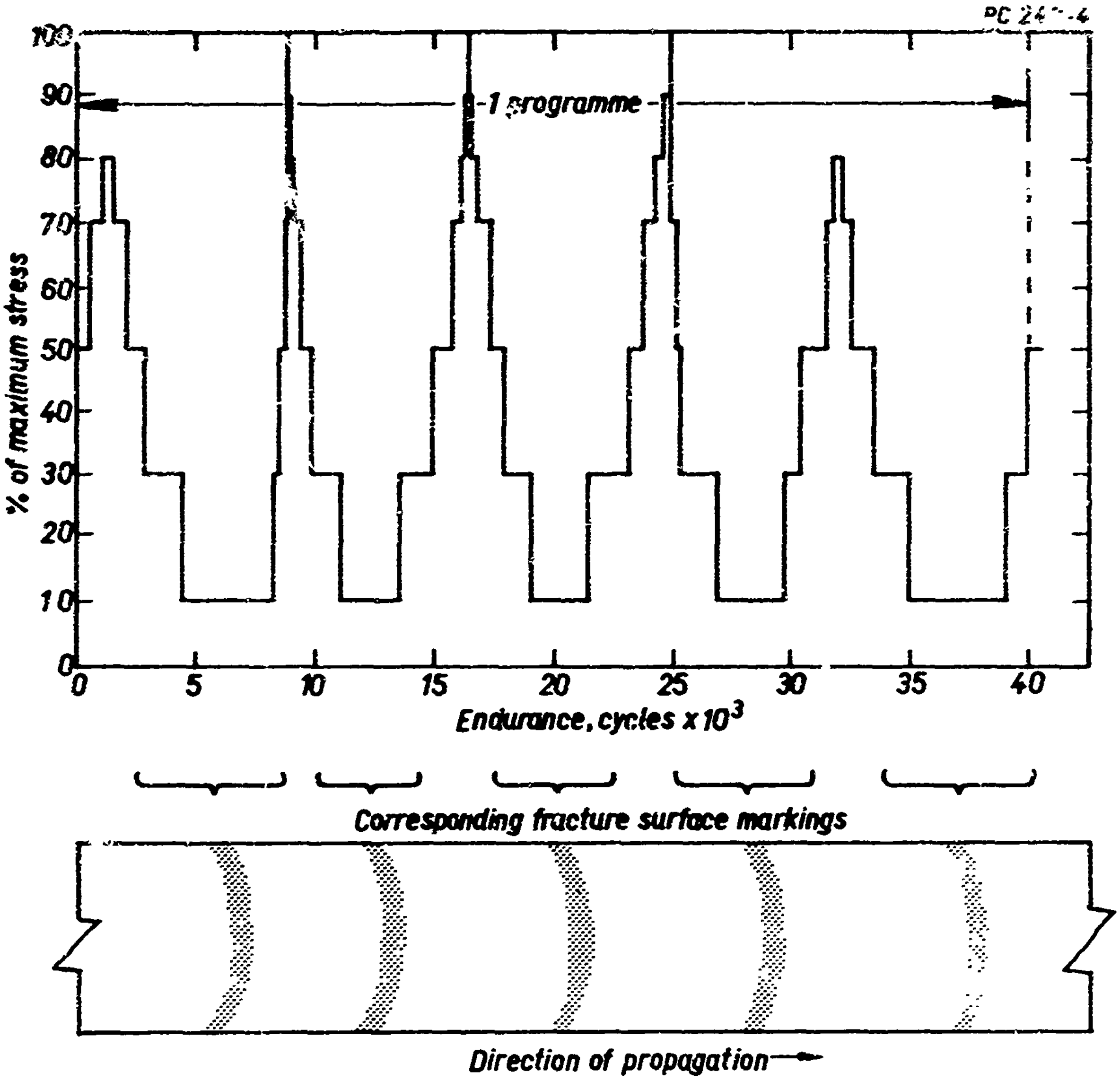


Fig.C6. Sketch showing the positions of the dark fracture surface markings in relation to the applied loading programme.

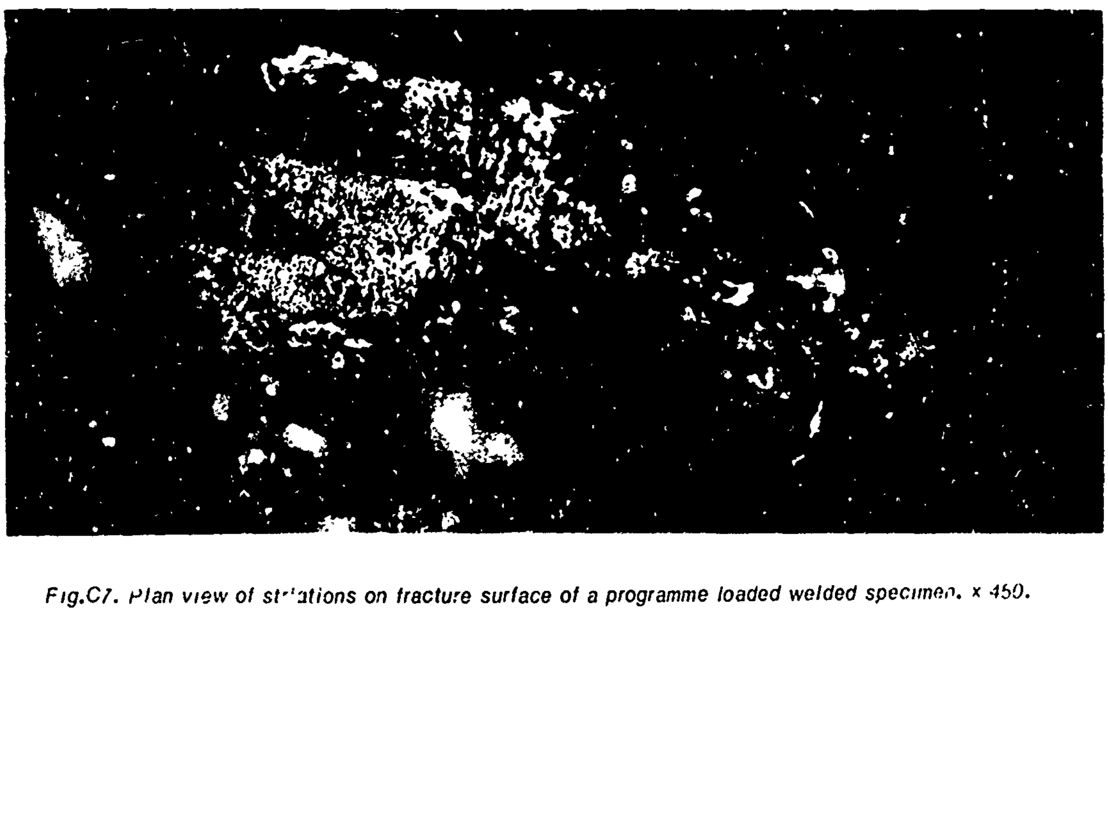


Fig.C7. Plan view of striations on fracture surface of a programme loaded welded specimen. x 450.

Fig.C8. Fatigue structures in Al:Zn:Mg alloy as seen in the scanning electron microscope, × 2500.

Fig.C9. Fatigue structures and sub-striations in Al:Zn:Mg alloy seen through the scanning electron microscope, × 9500.

TECHNICAL NOTE NO. 6/70 March 1970

PROGRAMMED LOAD FATIGUE TESTS ON NOTCHED AND WELDED SPECIMENS OF Al.Zn.Mg ALLOY

The report described constant amplitude and programmed load fatigue tests on notched and welded specimens in two high strength aluminium-zinc-magnesium alloys. It is shown that, with very few exceptions, the Miner-Palmgren hypothesis that $\Sigma\frac{n}{N} = 1$ consistently underestimates life. For the notched specimens using the basic quadratic programme $\Sigma\frac{n}{N}$ varied from 0.8 to 14.8. For welded specimens using the same programme the value of $\Sigma\frac{n}{N}$ varied much less and was approximately 2.6 to 7.0 for pulsating tension loading. Changes in the order of application of programme blocks had a negligible effect on the values of $\Sigma\frac{n}{N}$ obtained. However, both for half tensile and for alternating loading, lower values of $\Sigma\frac{n}{N}$ were obtained.

When a spectrum parallel to the constant amplitude S-N curve was used high values of $\Sigma\frac{n}{N}$ were obtained except when the lowest stresses in the programme were omitted. This fact led to the belief that a possible reason for the high values of $\Sigma\frac{n}{N}$ is coaxing at the lowest stress levels in the programme.

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